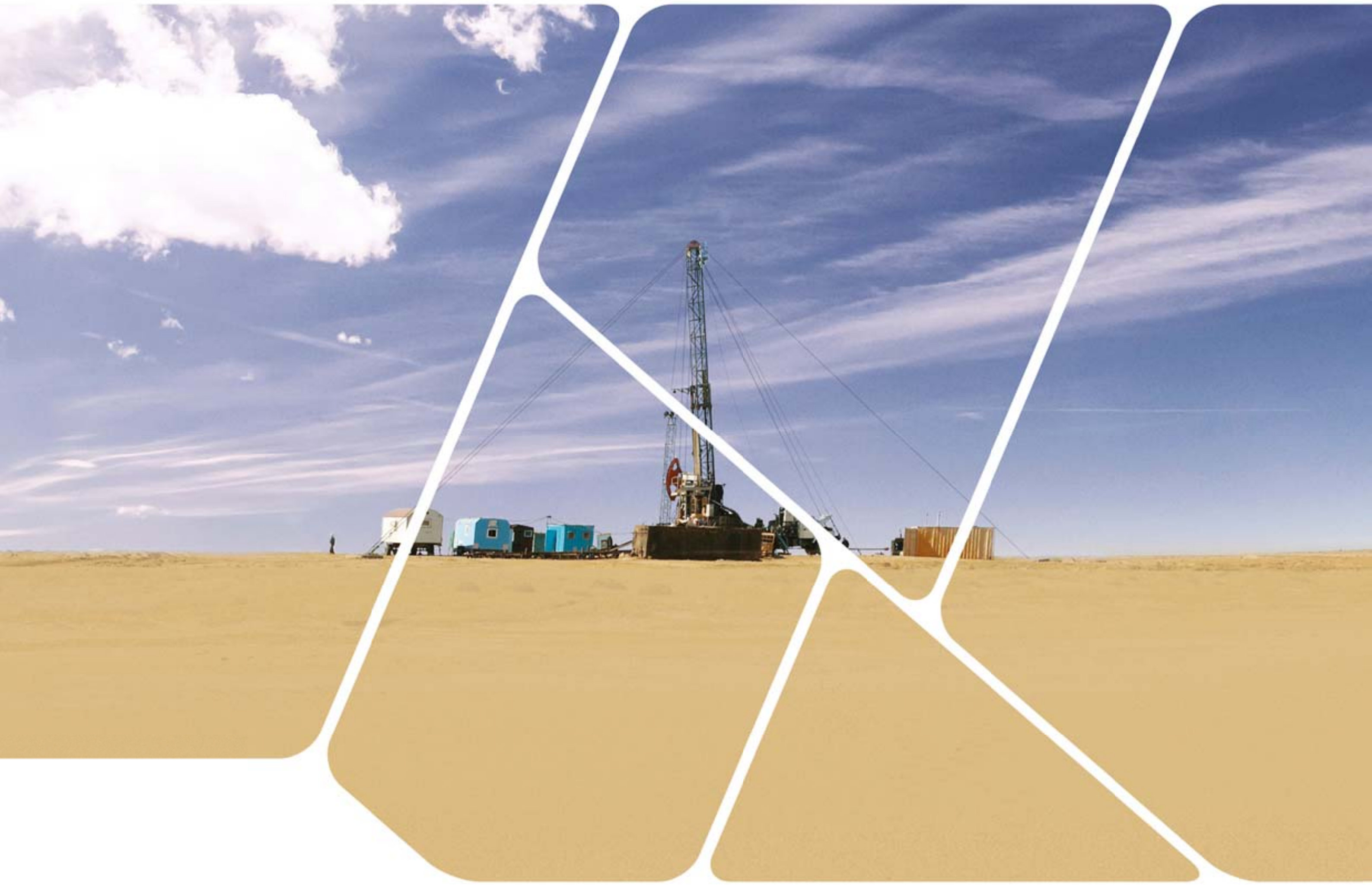


RESERVOIR ENGINEERING GRADUATE CERTIFICATE - *Week 1*

Introduction to reservoir characterization

A special course by IFP Training for REPSOL ALGERIA
Alger – October 30 - November 03, 2016

ifptraining.com

An IFP Training Course for REPSOL

Introduction to Reservoir Characterization

Alger , October 30 – November 03, 2016

Instructor: Laurence BOVE

IFP Training

Outlines

1. Objectives
2. Geological models versus Reservoir models
3. Cellular models
4. Data integration & Geological characterization workflow
5. Reservoir uncertainties
6. Overview on seismic interpretation
7. Qualitative well-log interpretation
8. Reservoir characterization *Facies analysis - Clastic environments*
9. Rock typing
10. Principles of petrophysics
11. Reservoir heterogeneities
12. Reservoir characterization
13. Reservoir modeling
14. Conclusion

1. Objectives

Integrated field development project: Objectives

- ▶ **3D geological models**: to help make relevant business decisions
- ▶ **Flow simulation models**: to predict reservoir performance

→ **Production prediction**: to plan capital expenditures, including

- Drilling new producers and injectors (infill design)
- Dimensioning & design of surface facilities (pipelines, crude & gas storage, water treatment,…)

→ **The right man is the Reservoir Engineer**

→ **A good reservoir model must integrate geological constrains**

Objectives of your company

- **Main goal after a new discovery:**
  - To ensure field development project is economically profitable
  - → **Plan adequate field development to optimize recovery**
- **Throughout field life:**
  - To acquire relevant information to monitor reservoir behavior
  - → **Use recorded information to optimize production recovery**

→ The proper way goes through reservoir modeling : → The right man is the Reservoir Engineer

- **The optimal profitability of a project requires the knowledge of:**
  - The volume of in-place hydrocarbons
  - The recoverable reserves (several scenarios)
  - The expected well performance (daily production)

→ The proper way goes through geological modeling : → The right man is the Reservoir Geologist

Reservoir simulation objectives

- **End product of geological models = starting point for reservoir simulation**
- **Reservoir simulation = numerical simulation of both production and injection history of a field**
- **Models use (as input recorded data):**
  - The production and injection rates (from all field wells)
  - The pressure changes over time
  - The volumes of produced oil and water

The **reservoir geologist** must check data consistency during modeling.

→ He needs to **work with every actor** of an integrated study.

2. Geological model vs. Reservoir model

Example of a field analog outcrop

Monterralo anticline (Colombia)

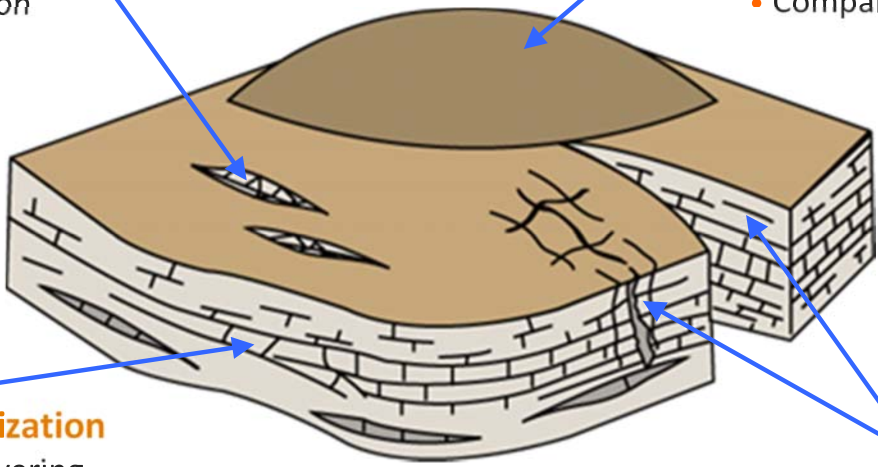
Nature is complex…

Image parameters of a hydrocarbon field

➔ Split a **complex problem** into several **simple ones**

4. Fluids in place
- Type of fluids, composition
- Fluid contacts
- Aquifer extension
- PVT, GOR

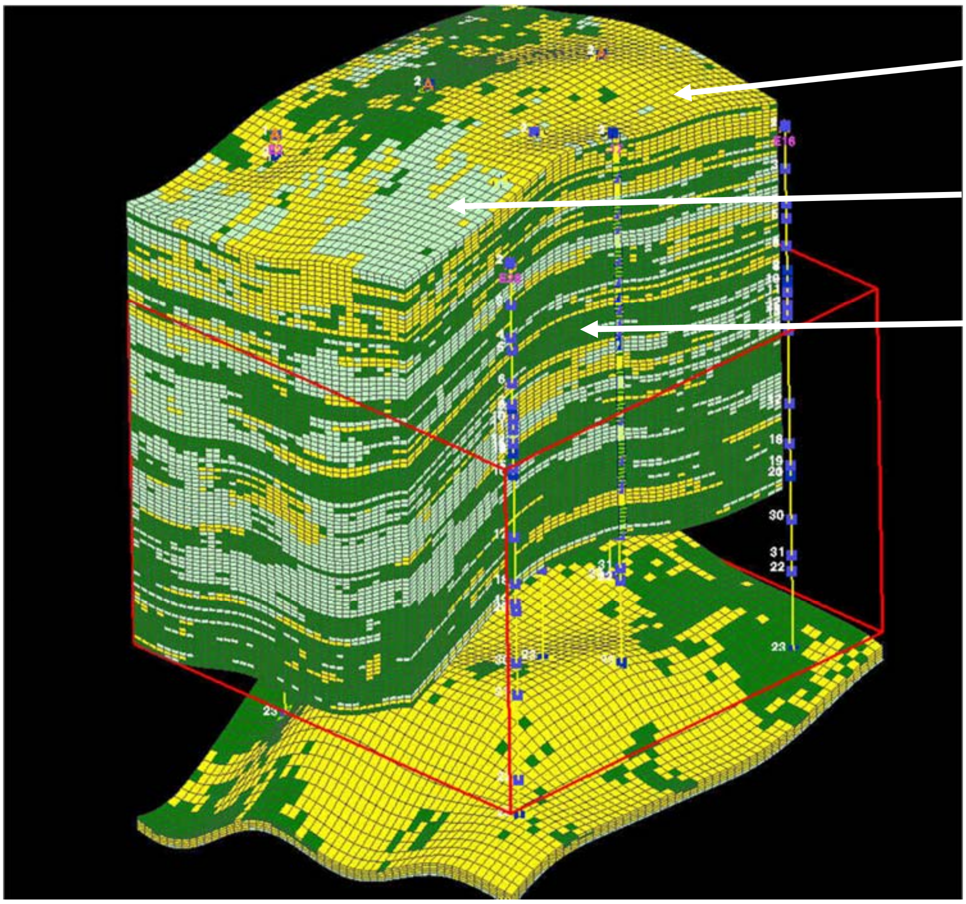
1. Shape & volume
- External envelope
- Iso contours (top-base)
- Compartments



3. Internal organization
- Correlations, layering
- Facies variation
- Petrophysics
- Drains, barriers (heterogeneities)

2. Structural framework
- Faults
- Fractured areas
- Micro fractures

Example of a geological model



Porous limestone

Tight limestone

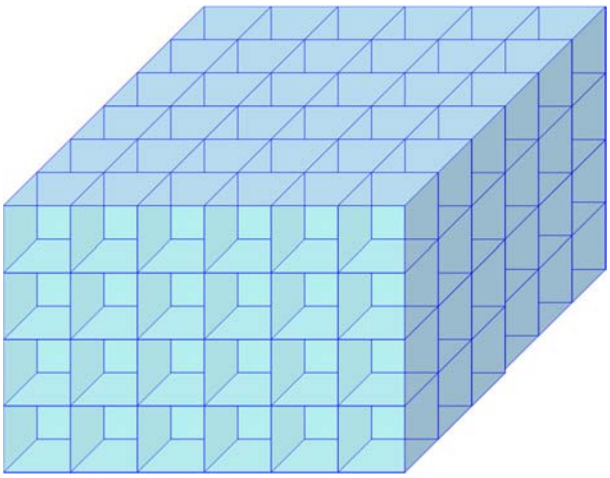
Shaly limestone

Geological model in carbonates

3. Cellular models

Geocellular model definition

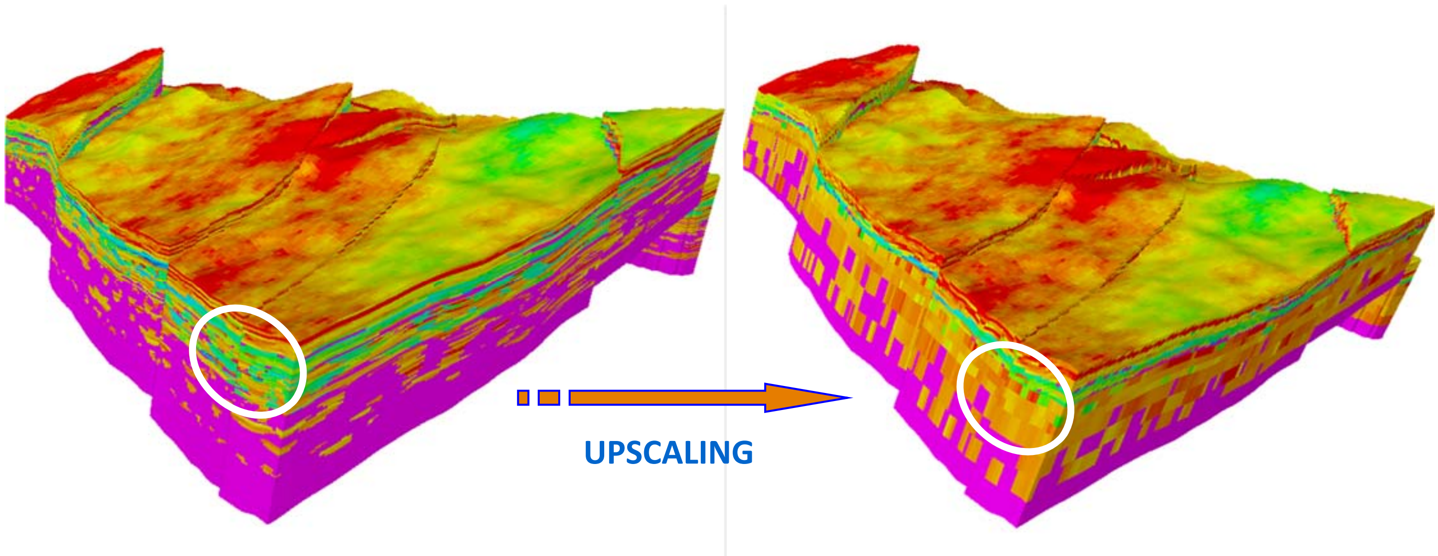
- A **cellular model** is a schematic description of a reservoir that represents its properties



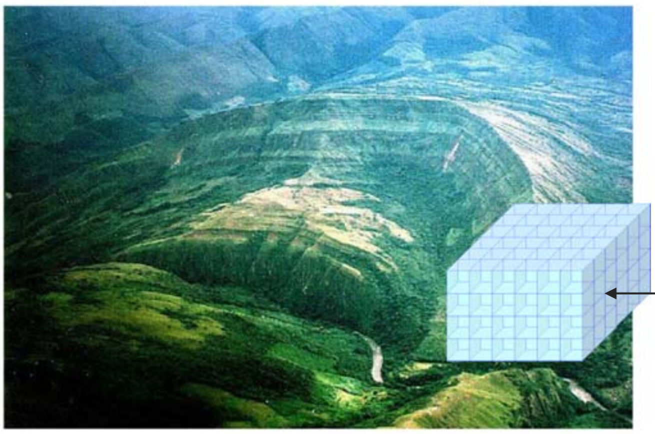
- **A cellular model is required:**
  - to understand the **complexity** of reality
  - to **quantify** reality
- **Modeling objectives: to simplify to quantify**
- **Upscaling: amplify** (integrated, global vision)

Vocabulary

- **Cellular models**
  - Geological model = Geomodel = **Static model**
  - Reservoir model = **Dynamic model**

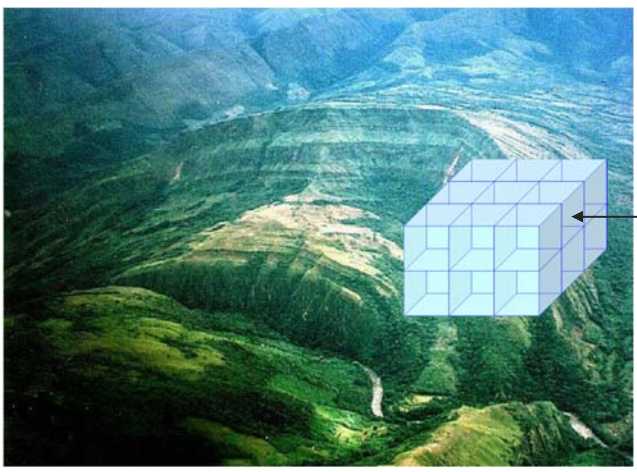


Geomodel vs Reservoir model – 1/2



Geological model (static)
for volume calculation

- **Net/Gross** thickness
- **Phi***e* (effective porosity)
- **K** (permeability)
- **S** (saturations: W, O, G)



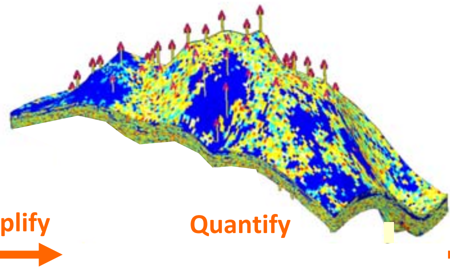
Reservoir model (dynamic)
for fluid flow simulation

Different objectives → Different cell size

Geomodel vs Reservoir model – 2/2

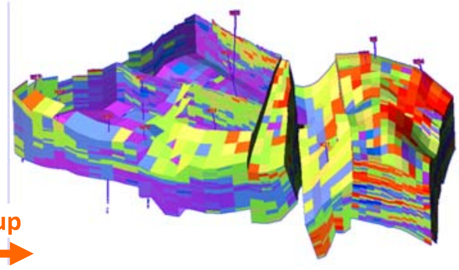
Reality	Geological model for **static** simulation	Reservoir model for **dynamic** simulation
	Characterize reservoir	Predict dynamic behavior

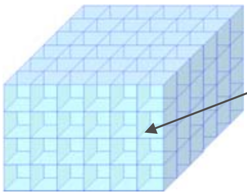
Simplify



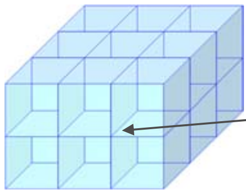
Quantify

Scale up





- N/G
- Phi*e*
- K
- S



- N/G
- Phi*e*
- K (Kx,Ky,Kz)
- S
- K*r*
- P*c*

- Quantitative synthesis
- One model for each parameter:
  - To understand hydrocarbons spatial distribution
  - To calculate accumulations in place

Not to predict the reservoir content

but **to anticipate**
its dynamic behavior

Upscaling: a challenge for information integration!

Reservoir model definition

- **A reservoir model is a grid of cells that makes it possible to manage and represent:**
  - Key heterogeneities (→ main flow units)
  - Lithofacies and petrophysical properties distribution consistency

The objective of a reservoir model is not to predict

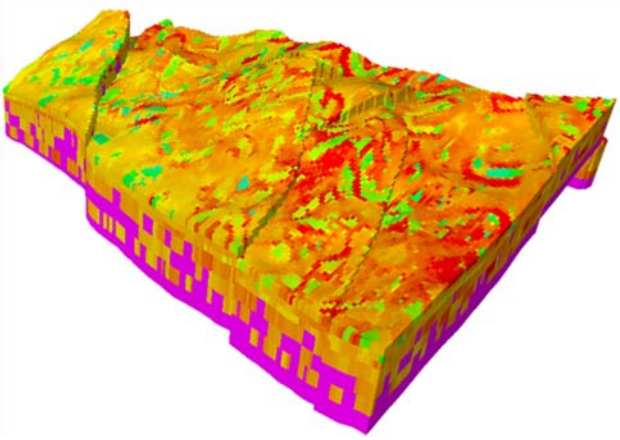
what we should find in the reservoir…

…but to anticipate its dynamic behavior

(i.e. match & predict both production & pressure,
and recommend appropriate actions)

A reservoir model: what for?

- A **reservoir model** is used to simulate the evolution of a field over **time**



- **Monitor & analyze:**
  - Well production
  - Fluid movements within the reservoir
  - Pressure evolution

→ **Anticipate**
= Predict + Recommend actions

Specificities of a reliable cellular model

- **A good reservoir model is strongly constrained by the geological model:**
  - Fluid flow simulation is more realistic and more reliable
- **A reliable geological model takes dynamic data into account :**
  - The identification of the main faults that impact fluid flow (either permeability barrier or conductive faults)
  - The stratigraphic barriers or multiple reservoirs

→ Need for a strong integration between geo-disciplines
(Geophysicists, Geologists, Reservoirs engineers) to ensure final model consistency (volume, pressure, rates)

4. Data integration & Geological characterization workflow

Characterization step

Main ideas

- **Perform data analysis to understand the reservoir before modeling**
- **Do not model anything if you do not have any idea of the results you want to reach!**

The key to success: Two steps

- **Two main steps**

  Characterization
  - Determine conceptual models for each discipline topic
  - Select relevant modeling parameters
  - Choose the modeling sequence (according to available data)

  Modeling

  Use the parameters resulting from characterization to build a numerical (digital, computed) model

- **Notion of conceptual model**
  - All geoscientific techniques can help to build conceptual models
  - Conceptual models help integrated team members reaching a global understanding of studied reservoir
  - Each preliminary model is related to parameters that will be used to populate the final numerical model

  - Make a conceptual model for each discipline topic, i.e
  - Prepare a table of table of uncertainties, at each step for each topic

→ **Time for modeling will be reduced**

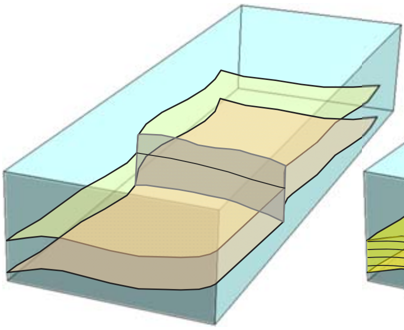
Tools for characterization

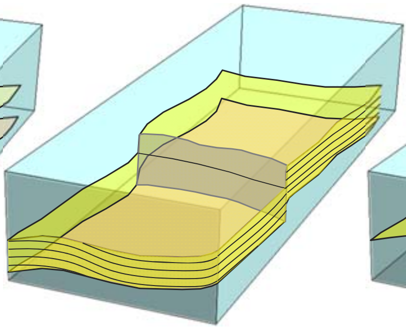
All tools for quality control and data analysis are reliable

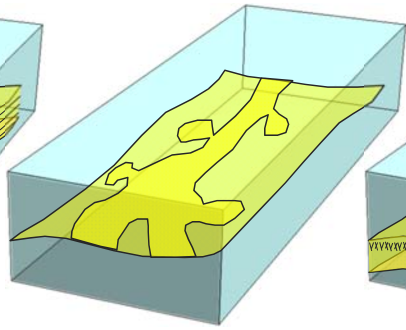
- **Geology**
  - Core description
  - Log analysis (correlation, sequence stratigraphy, electrofacies)
  - Statistical data analysis
  - Geostatistical data characterization

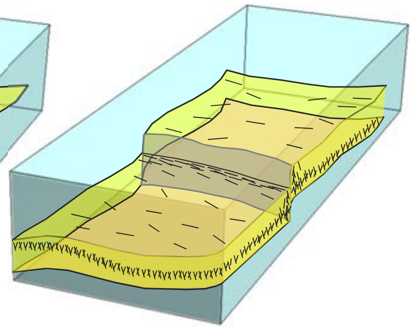
- **Geophysics**
  - Conventional seismic facies analysis
  - Seismic quality synthesis using geostatistics
  - Seismic facies analysis

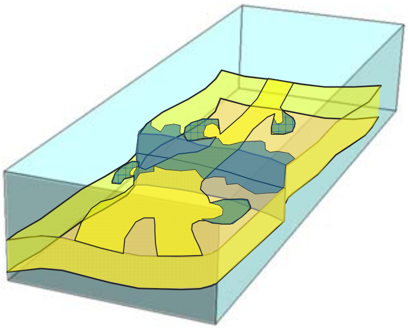
Conceptual model workflow

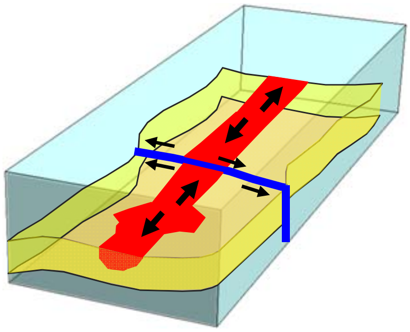

Structural model

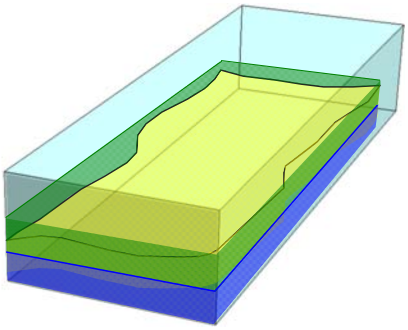

Stratigraphic model


Sedimentological model


Fracture model


Diagenesis model


Heterogeneity model (fluid flow)


Fluid model

Reservoir characterization and modeling - Key points

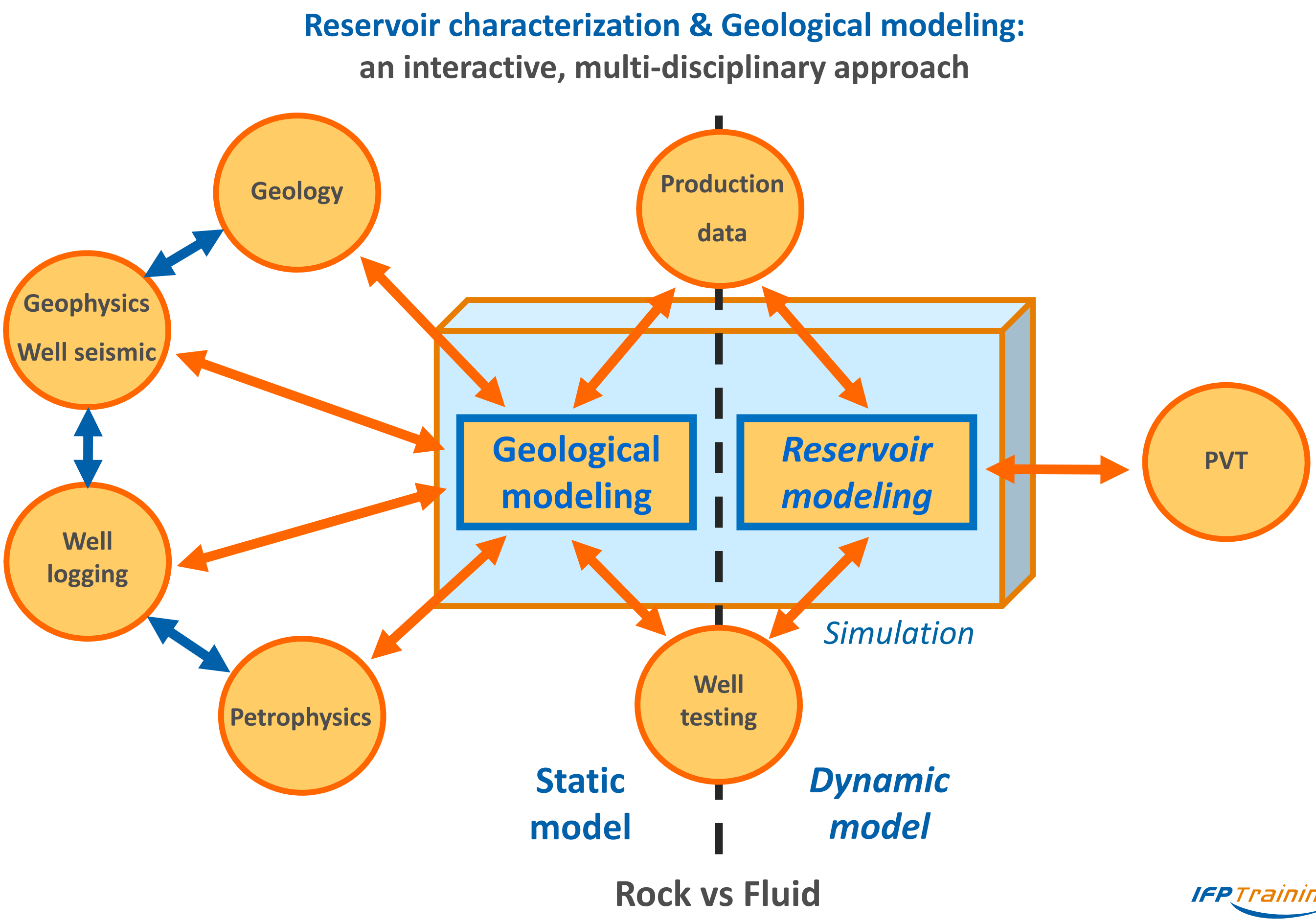
- **An integrated reservoir study requires a multidisciplinary approach that integrates complementary techniques**
- **Prior to the modeling phase, characterization must be completed, and conceptual models should be built for each discipline/specialty/topic**
- **Modeling**
  - **Use conceptual models at each step of modeling process**
- **Describe each item with simple words**
  - e.g. faults:
    - Main faults are oriented N-S → Define dynamic compartments.
    - Secondary faults are oriented N45, without throw but with fault-related open fractures → Probable positive impact on dynamic behavior.

Part A: Geological characterization
Static data integration

Static data integration workflow

- Database: a multidisciplinary approach
- Data integration
- Data analysis
- Type of data
- Understanding the data
- Quality control

Data base: Complementary modeling techniques



Type of Data: Dynamic data

- **Well tests**
  - Evaluate [K.h]: average permeability of drained area around the well
  - Estimate the distance to flow borders (interference test)
- **Static pressure measurements**
  - Identify connected blocks
- **Production history**
  - Estimate OHIP with the Material Balance method
- **Capillary pressure curves for each facies**
  - Evaluate the impact of Pc on permeability and recovery

Type of Data: Seismic data

- **Horizons**
  - From seismic picking (after time-to-depth conversion)
  - Good lateral definition but poor vertical accuracy
  - From 12.5 to 25 m in XY, ~ 3000 m/s * 4 ms = 12 m in depth
- **Faults**
  - From seismic picking (after time-to-depth conversion)
  - From 2D structural mapping
- **Seismic attribute maps (Net-to-Gross, average porosity, coherency…)**
  - Generate maps from seismic amplitudes, seismic attributes (both surface and volume) and calibrate them with well data
- **Seismic facies maps**

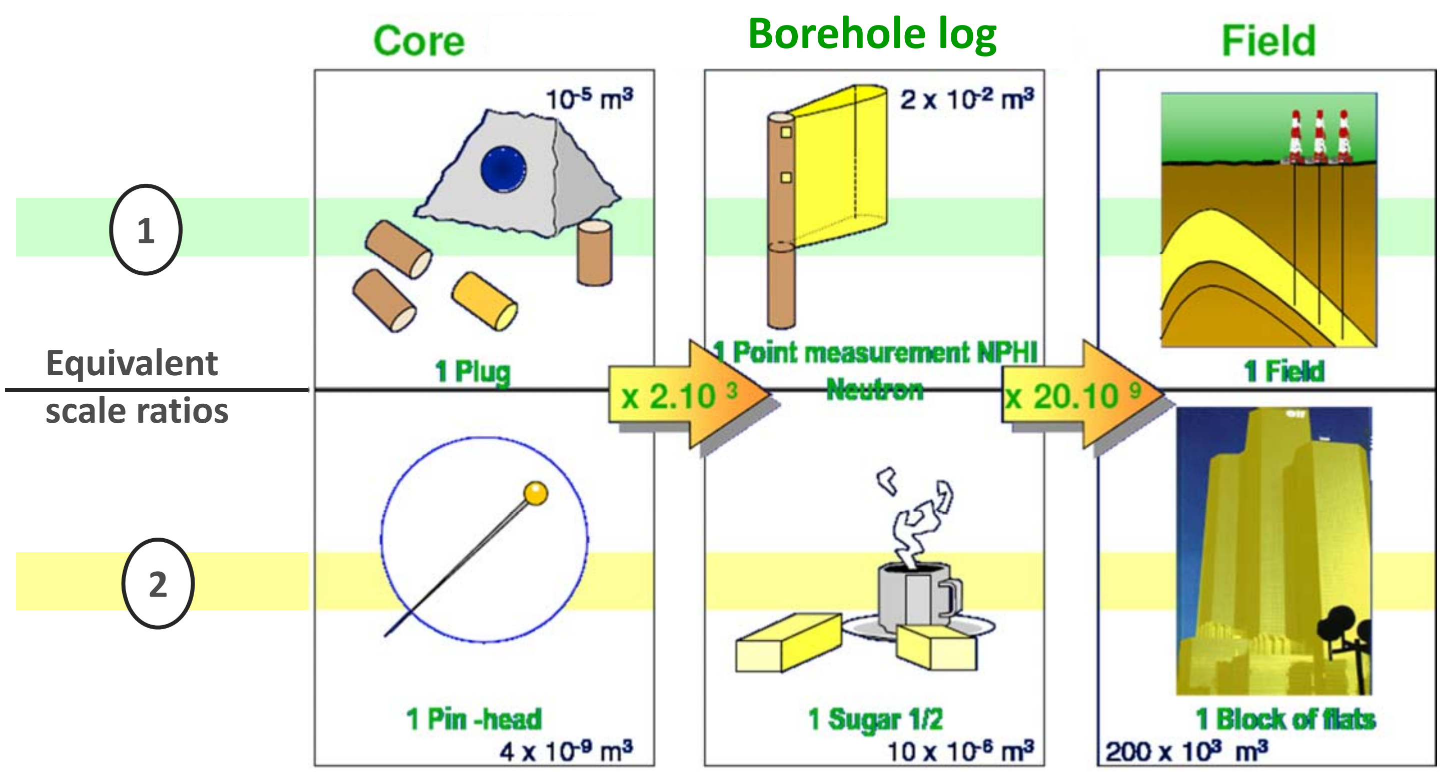
Type of Data: Well data

- **Well path in MD azimuth (converted to X, Y, Z)**
  - Accurate only in vertical wells or GPS measurements
- **Logs used for modeling**
  - **Porosity**: from NPHI-RHOB or SONIC logs and cores
  - **Permeability**: from PHI logs and cores
  - **Saturation**: from Resistivity logs and cores
  - **Facies**:
    - genetic (i.e. geology-oriented: lithofacies from cores)
    - rock types (i.e. petrophysics-oriented: petrofacies from SCAL)
- **Isochores/Isopachs**
  - From intermediate well markers
  - Generally smooth surfaces

Understanding the data: types and specificity

- **Different scales**
  - Plug data (5 cm) vs seismic bin (50 m)
  - K from logs vs [K.h] from well test
- **Different definitions**
  - Seismic data: **good lateral** definition but **poor vertical** resolution
    (1 sample every 10 m)
  - Well data: dense vertical sampling but very local (laterally limited)
    (1 sample every ft or ½ foot)
- **Different interpretations**
  - Facies definition: Geology (lithoFacies) vs Petrophysics (PetroFacies)

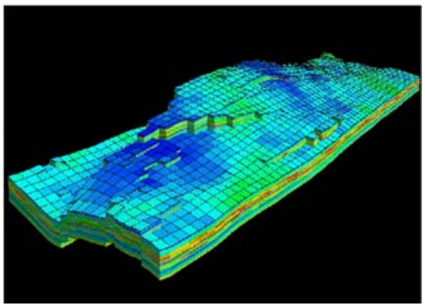
Scale ratio of data sets



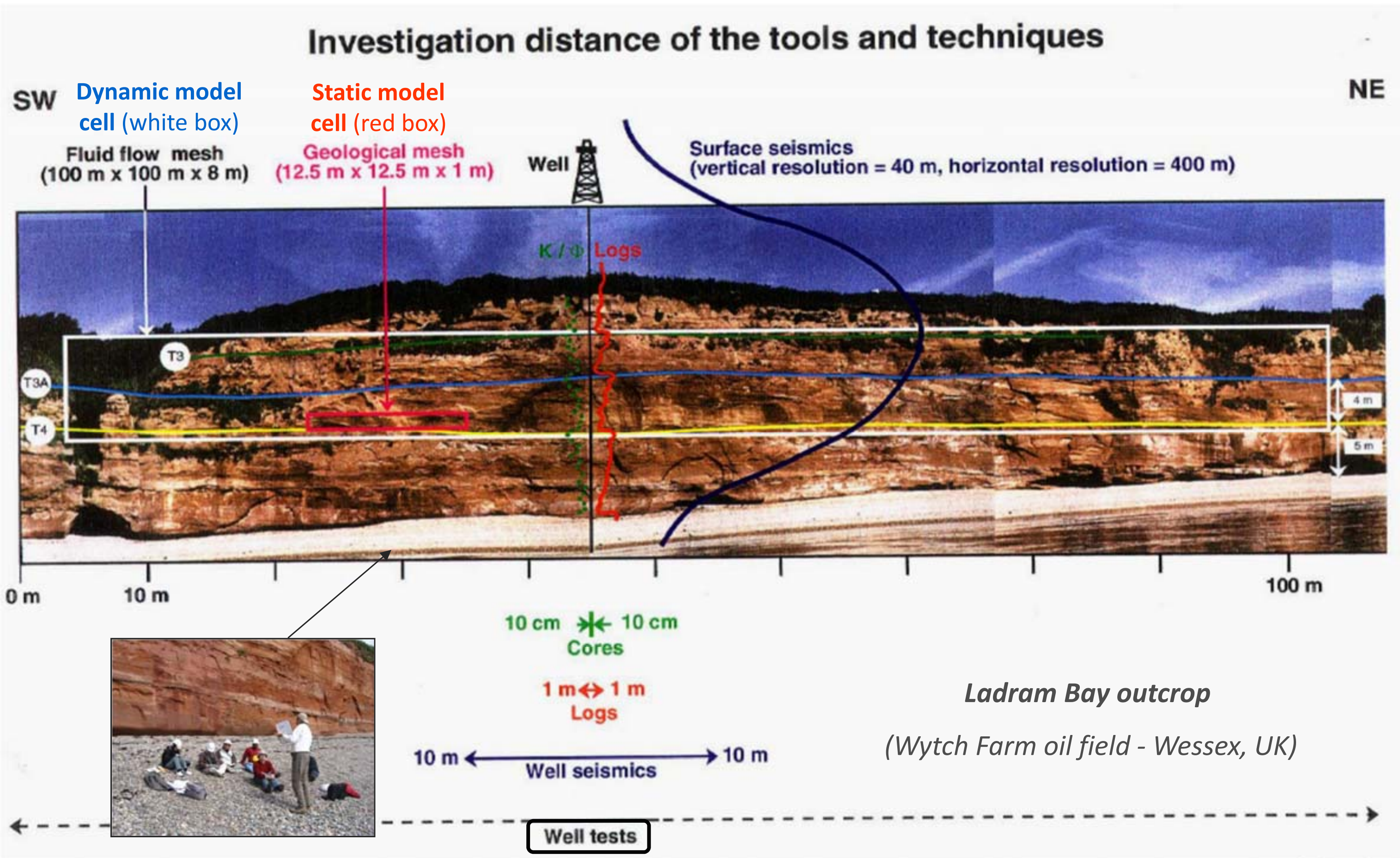
Representativity: well data vs field data scale

Haystack

Needle



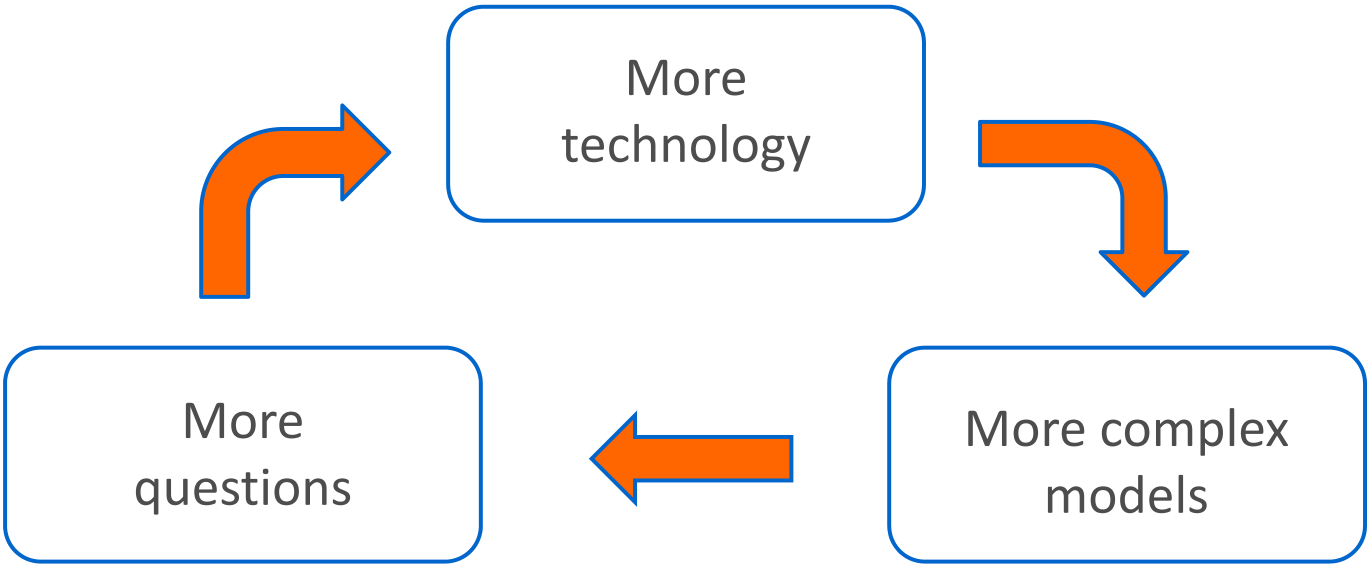
Comparing scales



Ladram Bay outcrop

(Wytch Farm oil field - Wessex, UK)

Complexification cycle



Do not make it endless: do stop at one point!

QC: Work with all your colleagues

To build a reliable summary document:

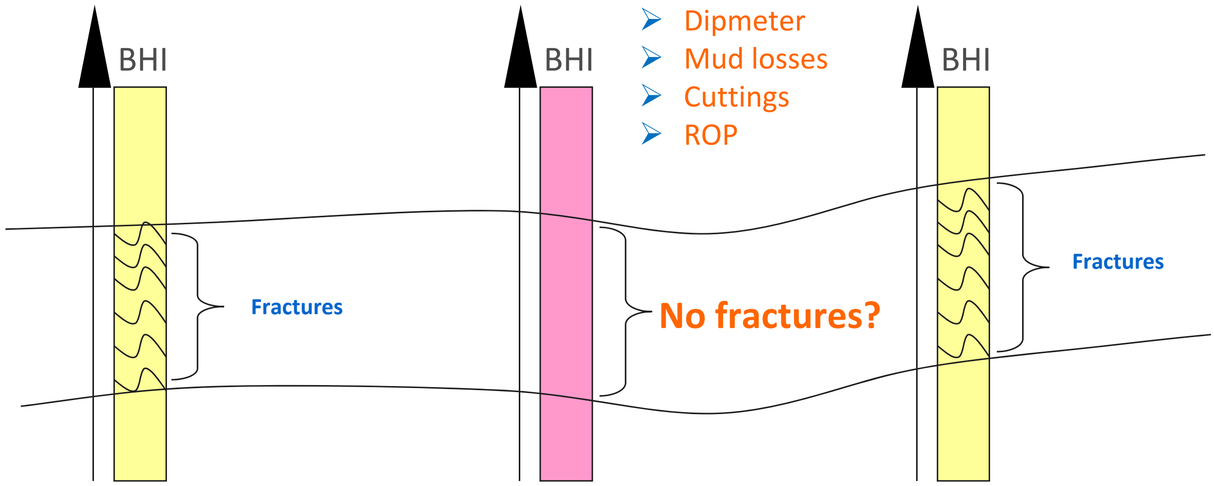
- **Make a detailed inventory of available data**
- **Perform a systematic, thorough data QC**
  - For a specific reservoir unit, a **good document** means a map with:
    - Seismic quality (area where seismic data is good, medium or bad).
    - Core quality
    - Always quality…

The reservoir geologist highlights areas where data are missing, or where they are of poor - or even bad - quality.

➔ QC = first step for managing uncertainty

Uncertainties on data

- **Any doubt or any problem identified on data during the QC phase may:**
  - Considerably increase the uncertainty level later in the workflow
  - Strongly bias the result reliability



Good quality   Bad quality   BHI = bore-hole imaging

Data integration for characterization - Key points

- **In an integrated reservoir study:**
  - **Data** are of various:
    - ✓Origins/Types
    - ✓Scales/Density
    - ✓Amounts/Volume
    - ✓Quality/Uncertainty
  - For each data type, specific **information** is gathered
    - ✓Some well intervals are cored, others are tested…
  - **Data** represent mainly **indirect** reservoir **information**
    - ✓Seismic data, Well logs, Dynamic data
    - ✓Direct access to the reservoir: only through coring ("ground truth")
  - Data only represent a **small proportion** of the reservoir volume
    - ✓Among the available data, well data are the most important (dense & accurate sampling)
  - The most crucial challenge: properly **integrate all information** within a consistent and relevant model – and reconcile all data types
    - **Upscaling**
    - **Geostatistics**

Part B: Geological characterization
Dynamic data integration

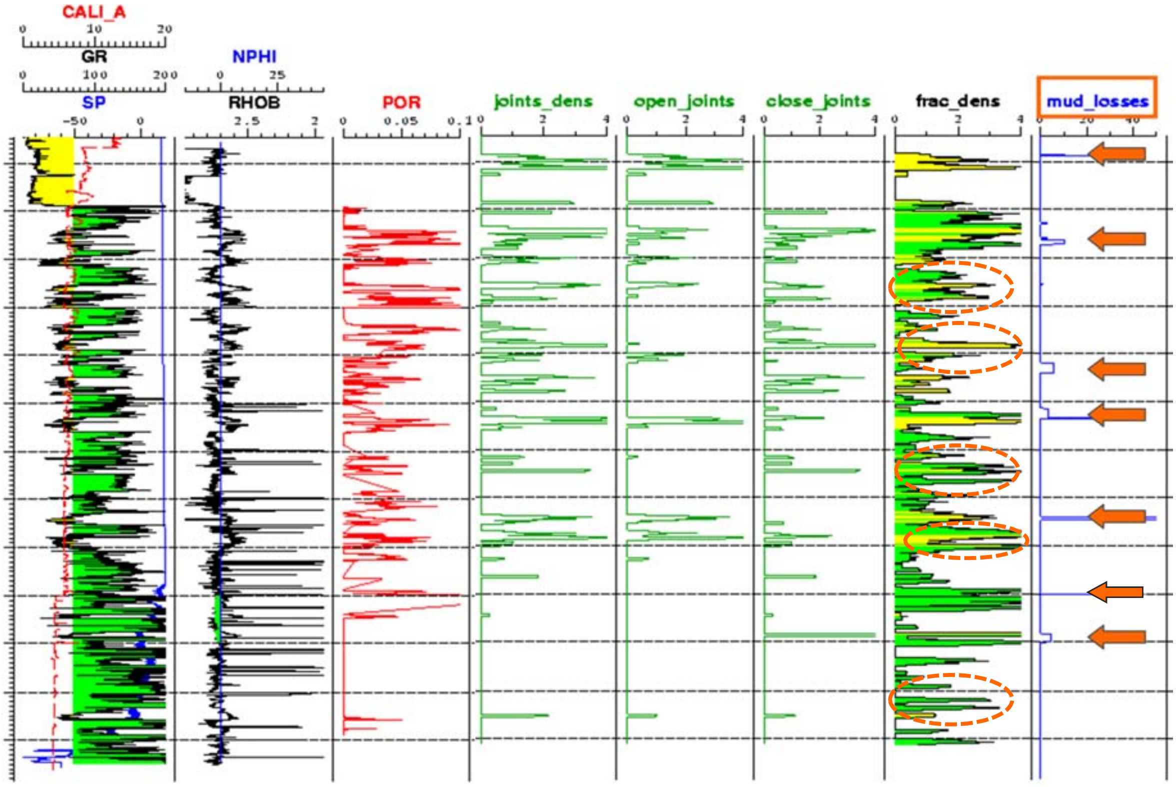
Dynamic data integration for characterization

- **Identification of reservoir heterogeneities based on dynamic data**
- **Dynamic data integration to enhance character detection**
  - Mud losses (drilling report)
  - Flowmeters (PLT)
  - Pressure measurements
  - Well test analyses
  - Production history (volumes) and water-cut evolution

Identification of heterogeneities affecting fluid flow

- **To identify compartments, first determine:**
  - Horizontal barriers (stacked reservoirs)
  - Vertical barriers: fault compartmentalization
- **To detect fluid flow anisotropy, first identify:**
  - Conductive faults
  - Fracture swarms
  - Channels

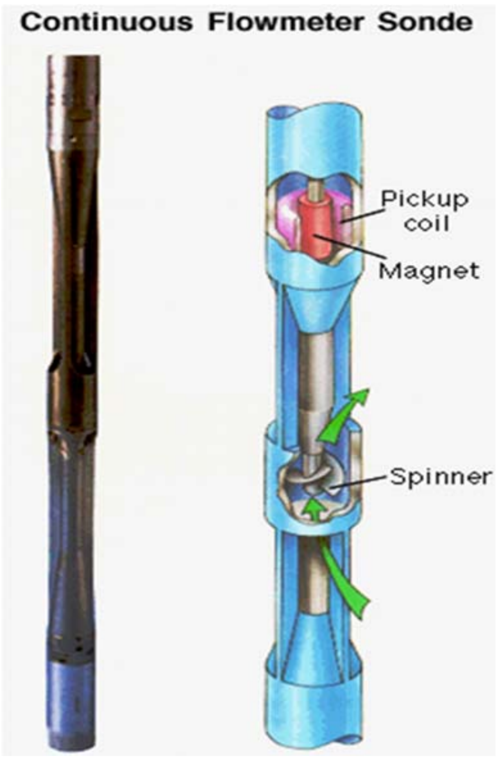
Mud losses analysis

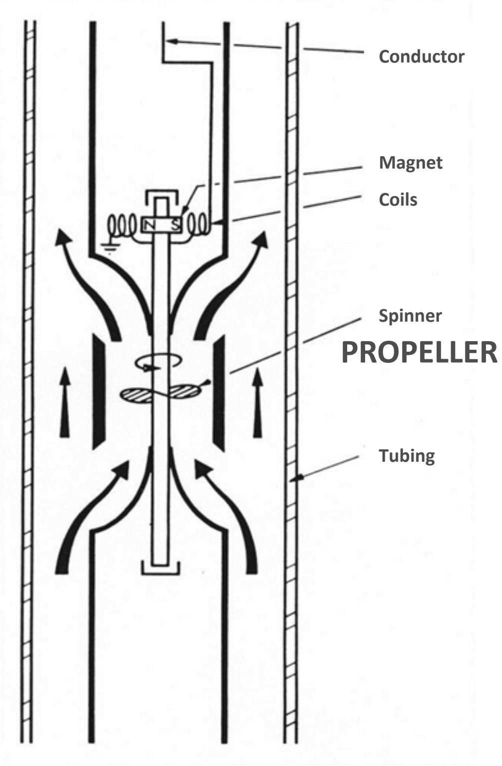


Karst? Channel? Open/Closed fractures? Fault?

Mud losses: 

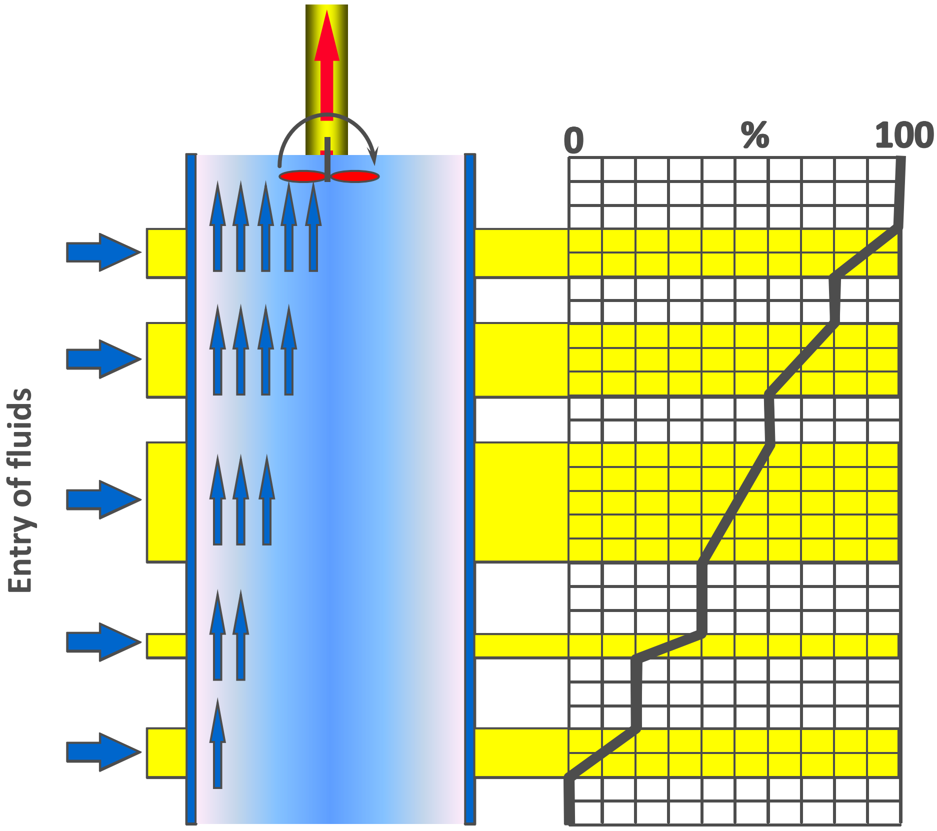
Continuous flowmeter: Production Logging Tool (PLT)





From Schlumberger

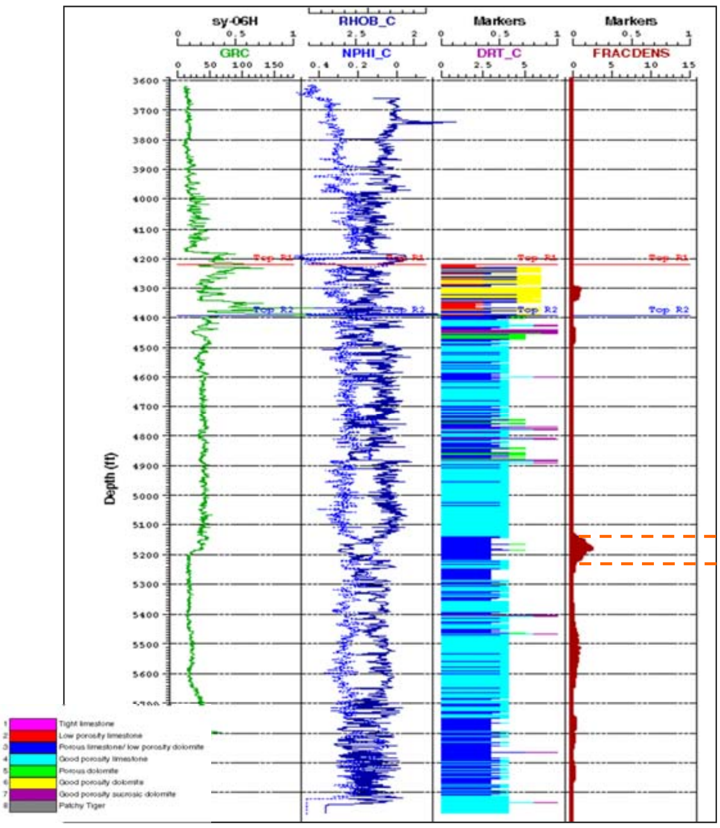
Continuous flowmeter (PLT)



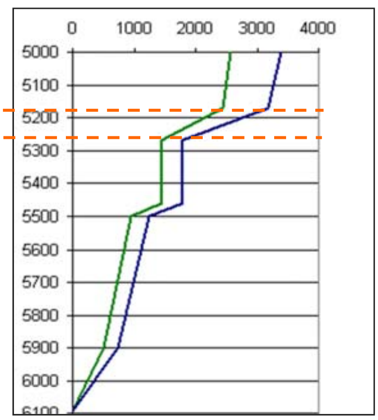
Cumulated contributions from each interval to total fluid production

Information from propeller speed measurement is converted to production (speed is proportional to flow)

Fault conductivity from flowmeter (PLT)



C_F ~ 70 Darcy.m

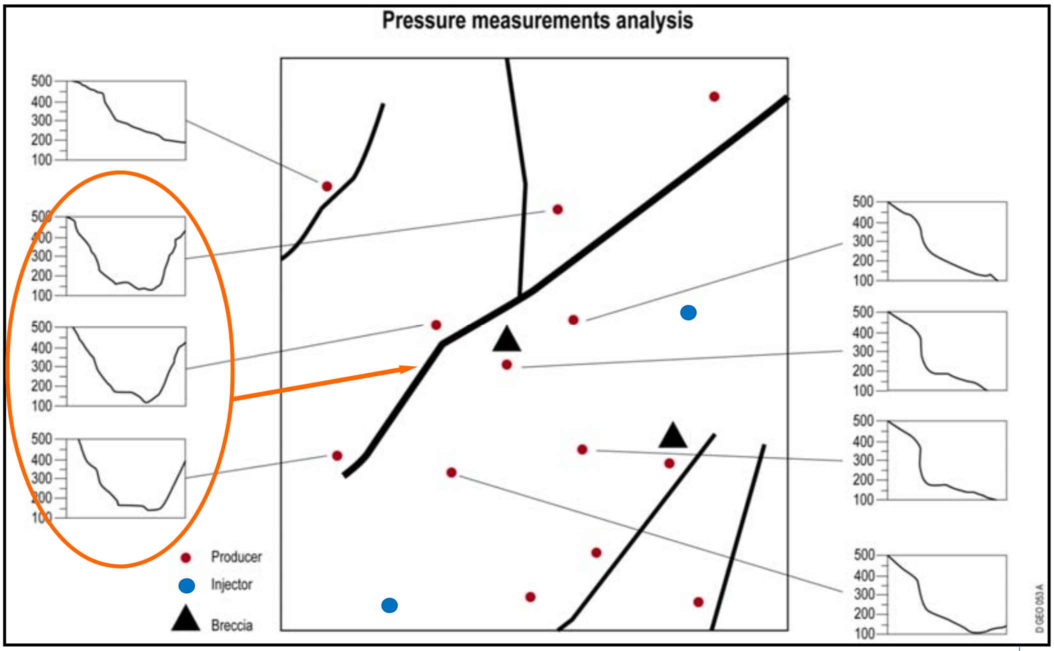


Pressure measurements analysis

- **Identification of dynamic barriers with pressure data**
  - A different pressure behavior between 2 groups of wells defines a permeability barrier that can be correlated with the presence of a conductive fault
  - *Note: GOR and water break-through data can also be used to determine preferential trends of hydraulic flow*

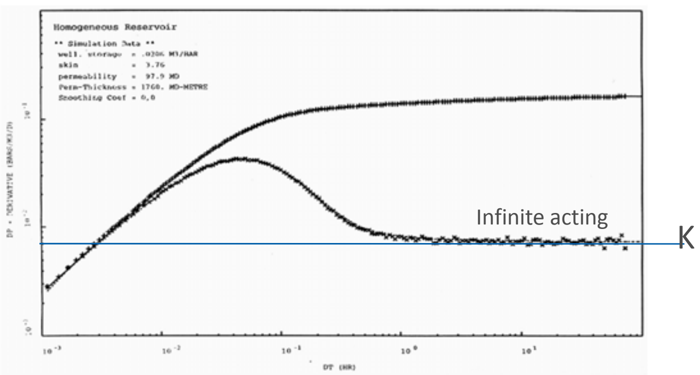
P^0 increase due to water injection conducted both by the fault and fractured zones

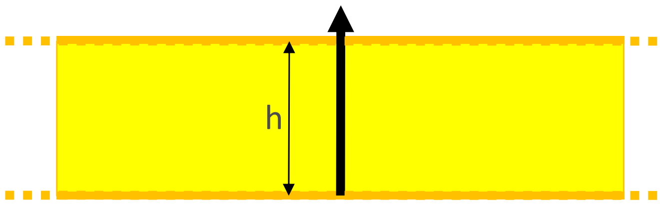
Breccia = fractures on cores



Interpretation of well test patterns

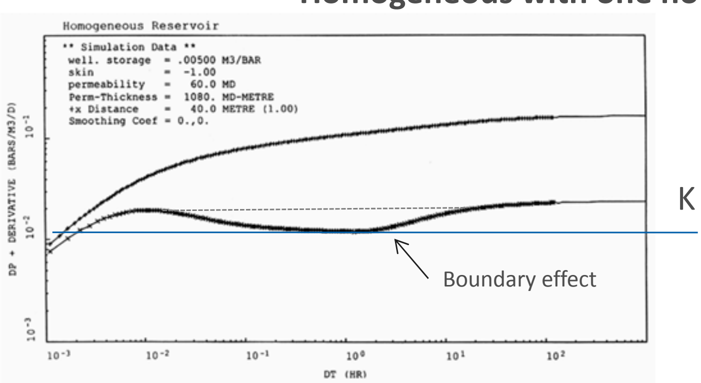
Homogeneous reservoir

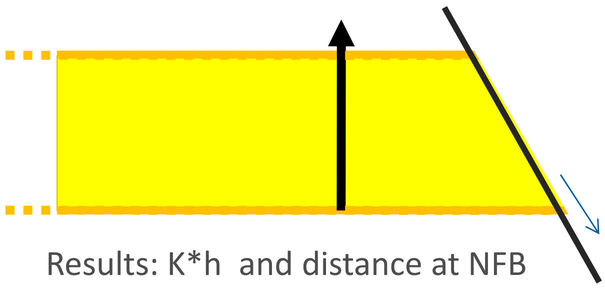




Results: K*h

Homogeneous with one no-flow boundary reservoir

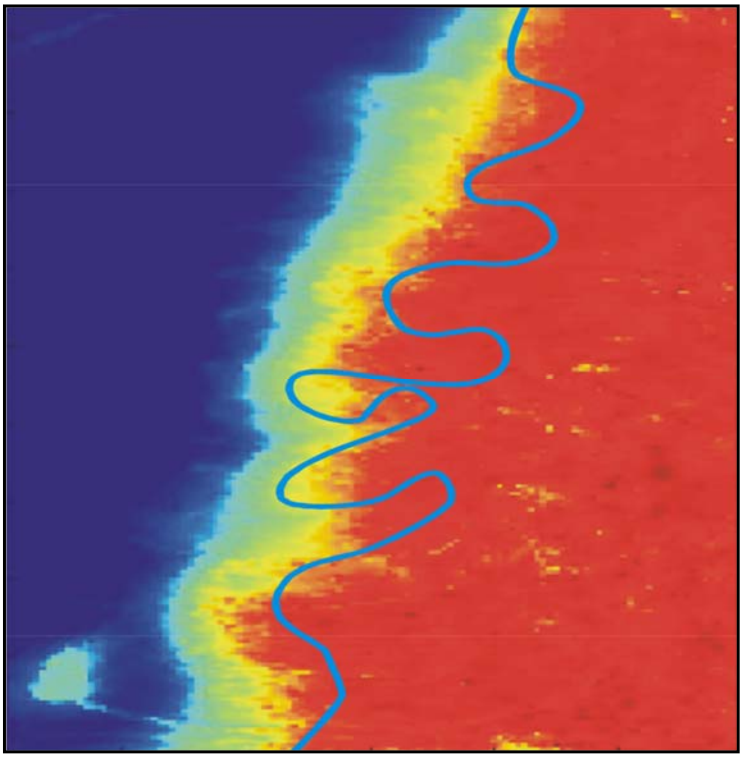




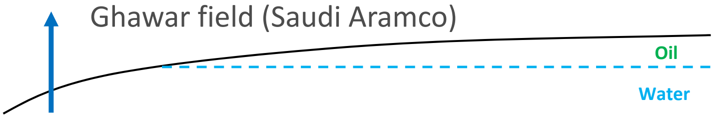
Results: K*h and distance at NFB

Production history and watercut analysis

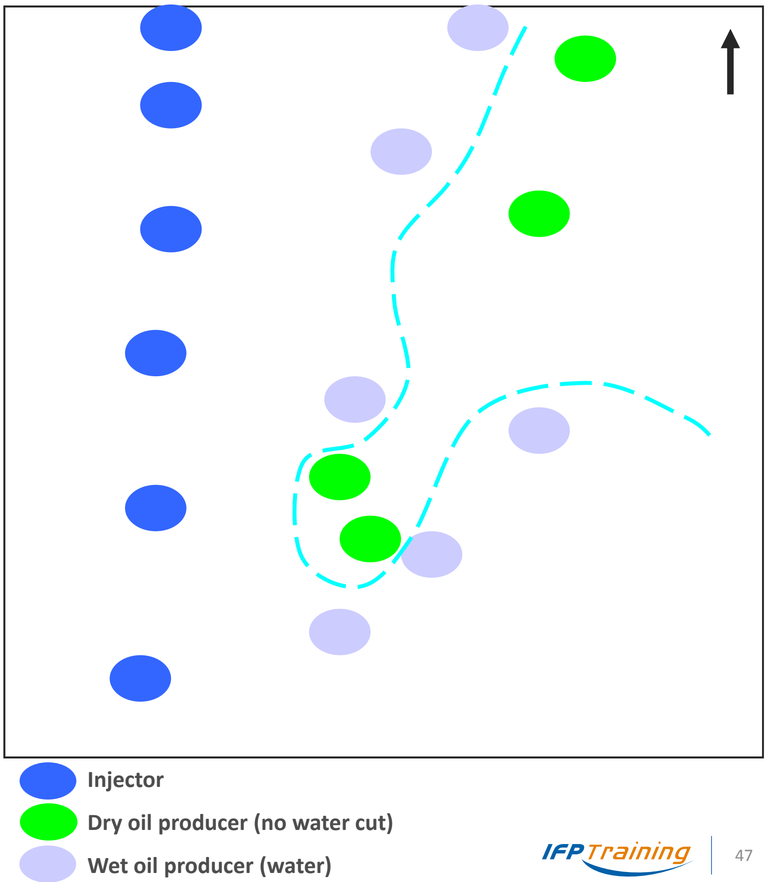
Break-through analysis for fluid flow anisotropy detection



Ghawar field (Saudi Aramco)



Fracture swarm identification



Dynamic data integration - Key points

- **Dynamic characterization is required to detect anomalies that impact fluid flow**
- **Identified anomalies are critical and must be incorporated into both:**
  - Geological model and
  - Reservoir model
- **An integrated team for a reservoir study has a common objective: i.e. to build a conceptual model**
- **This model should integrate both sedimentological and structural elements in order to explain reservoir anisotropy regarding fluid flow**

5. Reservoir uncertainties

About uncertainties

- **Introduction to uncertainties**
- **Uncertainties: two approaches**
  - Deterministic
  - Probabilistic
- **Managing uncertainty**
- **Reservoir model and uncertainties**
  - Static uncertainties (structural, stratigraphy, petrophysics,…)
  - Dynamic uncertainties
- **Uncertainties in reservoir characterization**

Uncertainties are to be considered

- **Uncertainties are everywhere!**
  - Complex physics
  - Lack of data
- **If not taken into account uncertainties can ruin a project**
  - Unexpected events…
  - → Should be defined by the team in charge of the project with the help of specialists

Assessing uncertainties

- **Unidentified or neglected uncertainties may result in a non-economical development**
- **One objective of reservoir monitoring is to help reducing dynamic uncertainties**

→ **Describing and understanding a reservoir is not an easy task (complex geology, data heterogeneity,...)**

Murphy's laws

Deterministic version

- **If anything can go wrong, it will!**
  - *The buttered side of the bread always falls face down!*

Probabilistic version

- **If there is a 50-50 chance that something goes wrong, then 9 times out of 10, it will!**
  - *The chance of the buttered side of the bread falling face down is directly proportional to the price of the carpet!*

Types of uncertainty

- **Uncertainties on data** — ✓ **Acquisition**
- **Uncertainties on interpretation (results)** — ✓ **Interpretation**
- **Uncertainties on characterization (synthesis, integration)** — ✓ **Integration**
- **Uncertainties on modeling (concept, numerical values)** — ✓ **Computation**

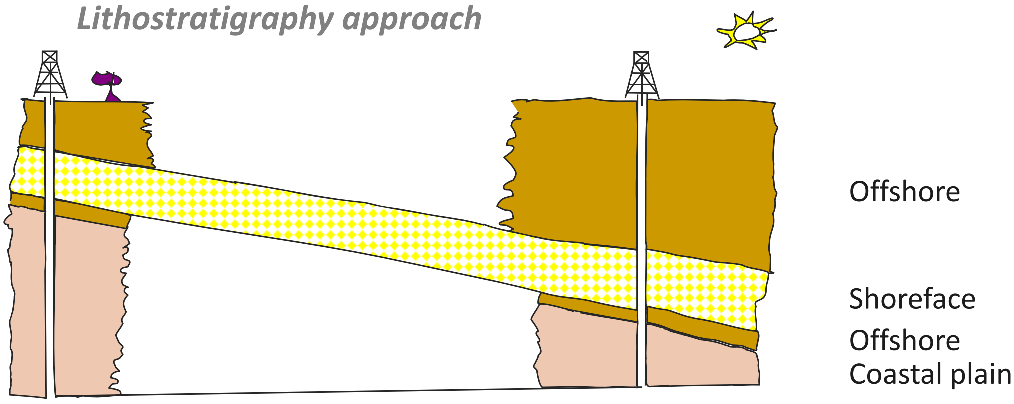
→ Uncertainties are additive!

Managing uncertainties

- **Uncertainties are present at each step of the workflow**
  - Structural (seismic)
    - Migration
    - Velocity model
    - Picking (faults & horizons)
    - Time-to-depth conversion
  - Geology
    - Sedimentological concept ; sedimentary bodies size, shape and distribution
    - Facies
    - Porosity, Permeability, Net thickness, Gross thickness, N/G, saturations (Sw…)
    - Fluid contacts
  - Dynamics
    - Fault transmissivity and related possible compartmentalization (different pressure regimes)
    - Permeability barrier extension
    - Kv/Kh
    - Fluid properties (μo, Bo, Bg, Rs, …)
    - Saturation functions: capillary pressure Pc and relative permeabilities Kr
    - Aquifers

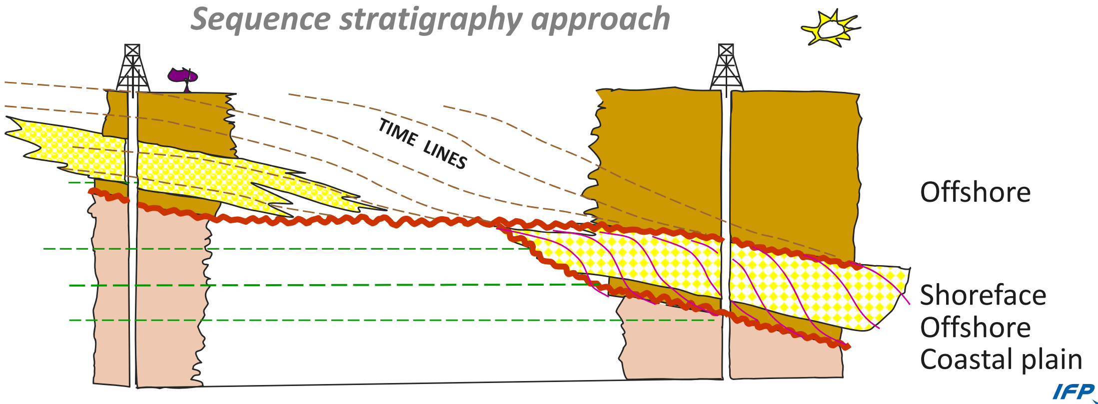
Uncertainties in sedimentological interpretation

Lithostratigraphy approach



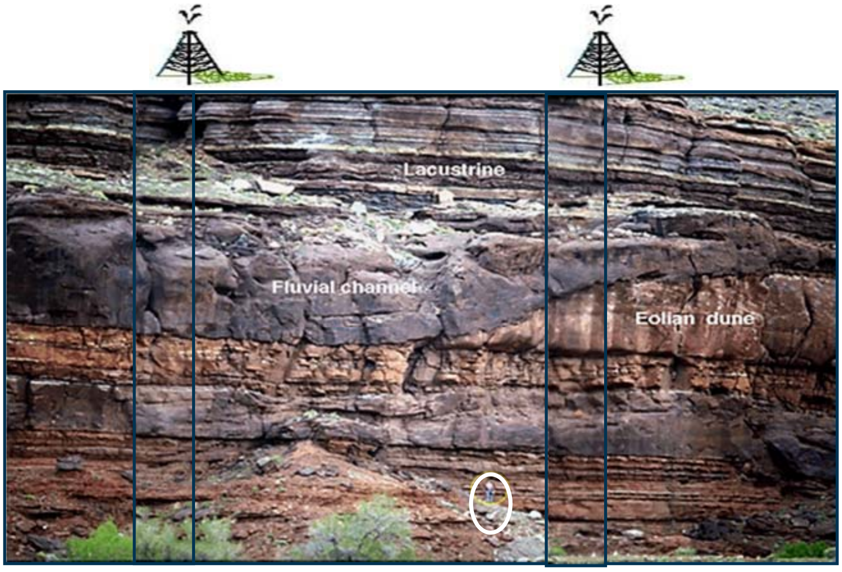
Good facies analysis but wrong sedimentological model: beware of correlations!

Sequence stratigraphy approach



Uncertainties in geological characterization

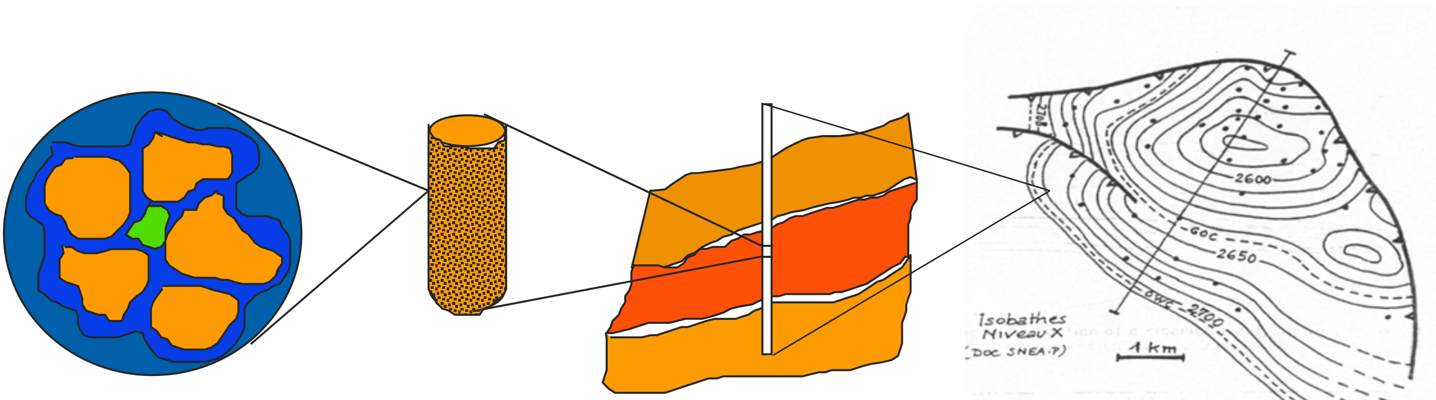
- **Main uncertainties in geological data are related to:**
  - Geological & sedimentological conceptual models
  - Petrophysical parameters:
    - porosity
    - N/G ratio
    - fluids saturations
    - fluids contacts



A geological model must represent spatial variability

Reservoir uncertainties

- **Uncertainties are related with:**
  - Available data (quantitatively- and qualitatively-wise)
  - Data interpretation
  - Reservoir heterogeneities
  - Scale changes

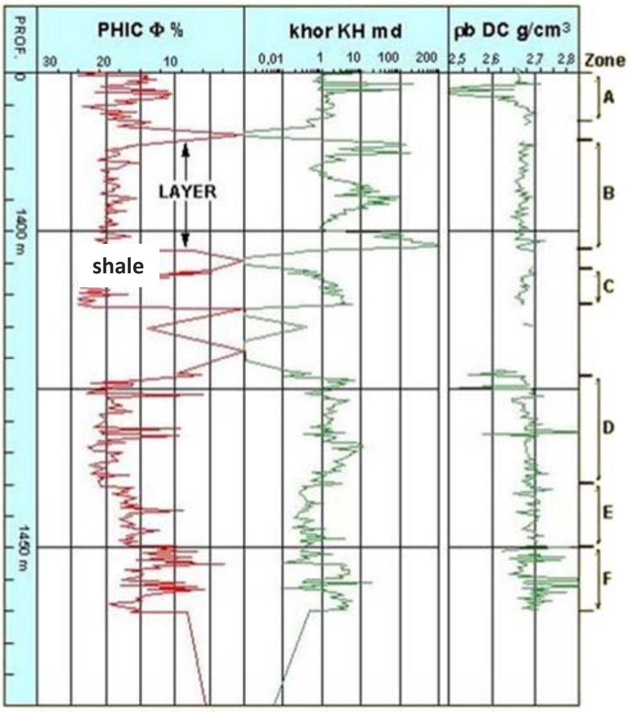


Pore scale	**Core** scale	**Well** scale	**Field** scale
1-100 µ	10 cm-10 m	50-500 m	1-100 km

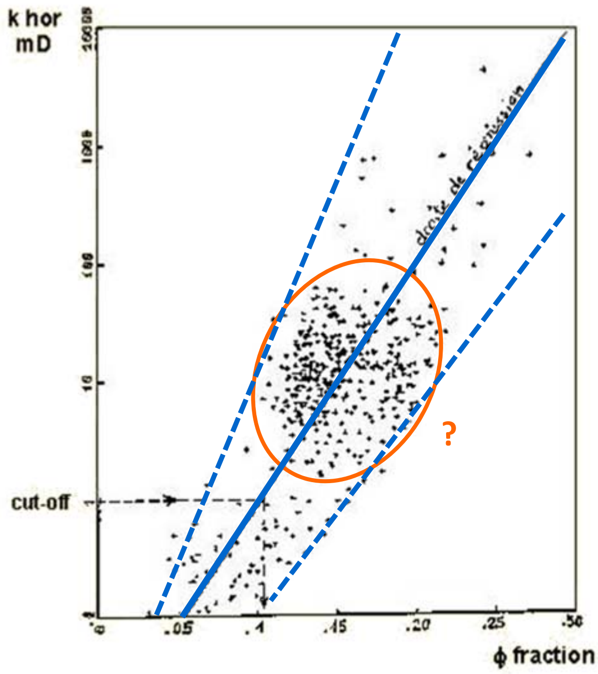
Uncertainties in petrophysical data

Uncertainty in petrophysical measurements

Core data

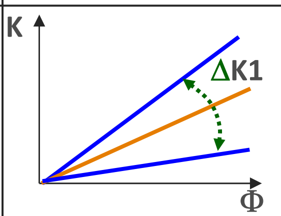
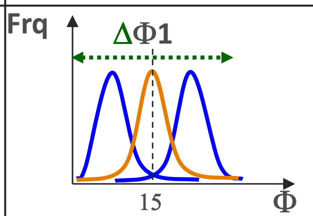
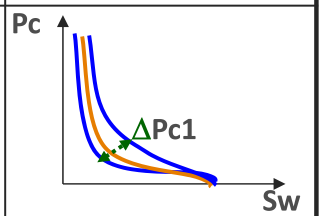
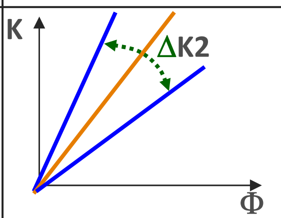
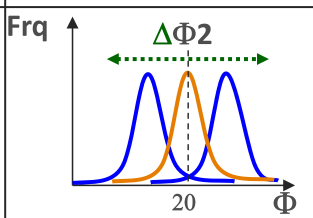
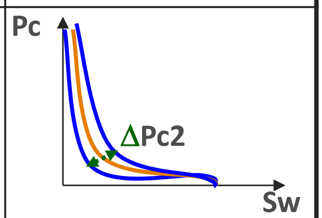


Log K vs Ø



Rock Types: integrating facies & managing uncertainties

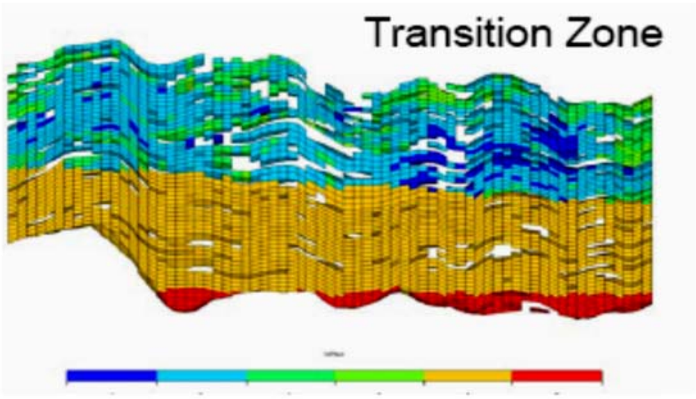
- **Rock Types result from the calibration of electrofacies with petrofacies**
  - RT are used to populate 3D geomodels

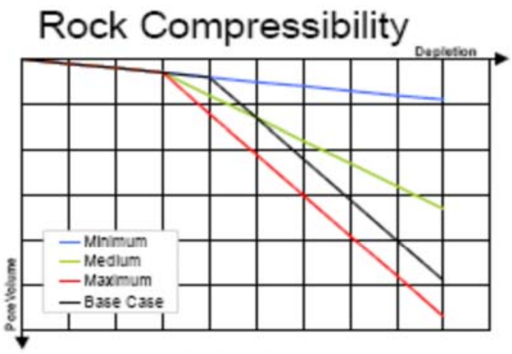
Rock Types	K	Φ	P_c
RT#1			
RT#2			
RT#3	. . .	. . .	. . .

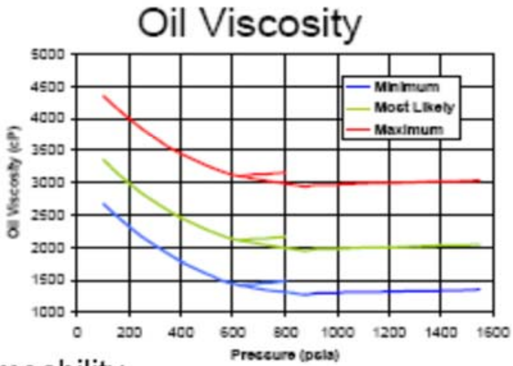
Rock typing = identification of homogeneous dynamic behavior

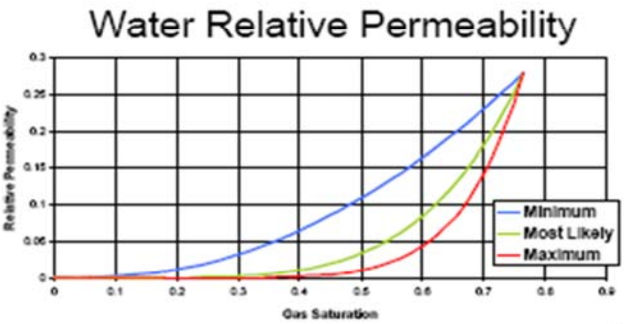
→ definition of **Flow Units** for dynamic modeling

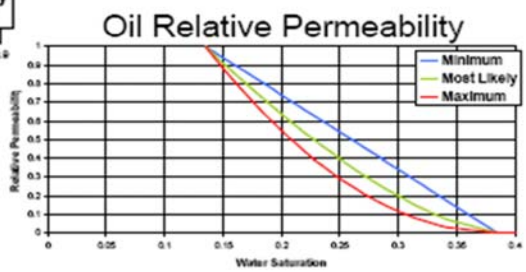
Uncertainty in dynamic modeling











Uncertainties in reservoir characterization - Key points

Geophysics	Geology	Res. Engineering
➢ Migration ➢ Velocity model ➢ Horizon picking ➢ Fault picking ➢ Time-to-depth conversion ➢ Well-to-seismic tying	➢ Structural and sedimentary concepts ➢ Extension and orientation of sedimentary bodies ➢ Distribution, shape, AE/RT limits ➢ Parameters: K, phi, NTG, Sw... ➢ Fluid contacts	➢ Fault transmissivity ➢ Extension of barriers ➢ Kv/Kh ➢ Fluid properties ➢ Pc and Kr shapes and end points ➢ Aquifers ➢ Rock compressibility ➢ Well PI

- **In a model, details in excess are not a guarantee of accuracy:**
  - **Uncertainties are additive!**
  - → Reduce the number of facies during the geomodeling phase

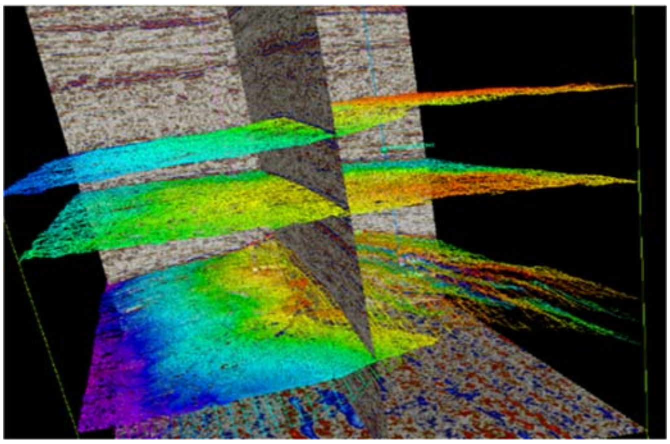
6. Overview on seismic interpretation

Seismic summary

- **Seismic interpretation objectives and deliverables**
- **Part A: Define trap geometry - Structural information**
  - Conventional seismic interpretation
  - Time-to-depth conversion challenges and issues
- **Part B: Extract information about the reservoir - Additional information on subsurface**
  - Seismic attributes
  - Seismic facies analysis

Objectives and deliverables

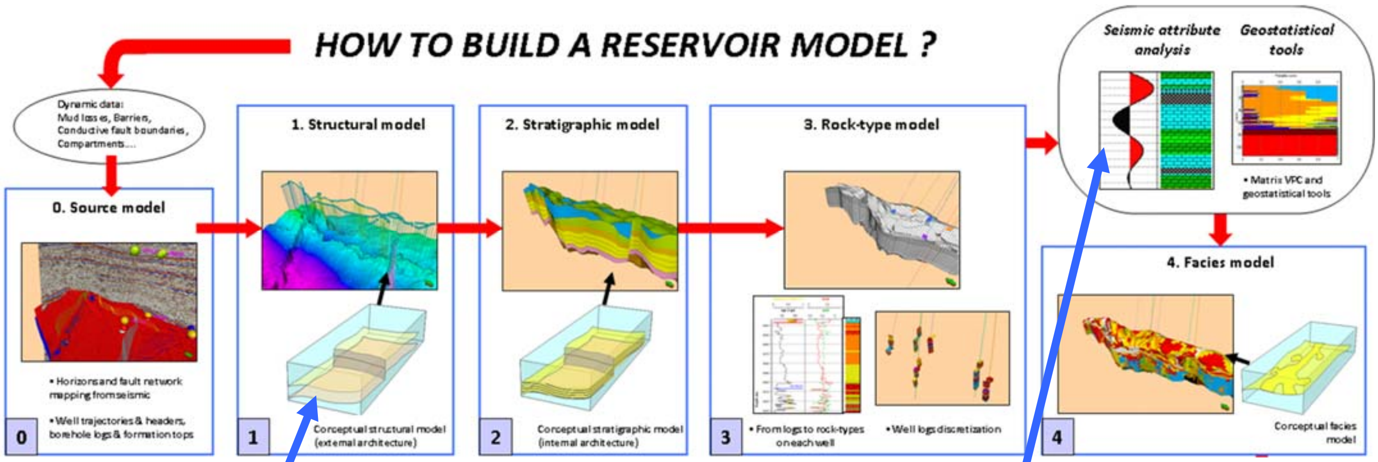
- **Seismic what for ?**
  - Structural and facies information between wells (reservoir framework: top and base surfaces) is extracted from seismic data



- **Seismic for reservoir architecture**
  - Structural maps and grids
  - Attributes maps and grids
  - Fault network, map and grids
- **Seismic for reservoir information: seismic data can be linked with the following parameters**
  - Fractures
  - Lithology/Sedimentological facies
  - Porosity

➔ **Deliverables are maps and grids**

Seismic information in characterization workflow



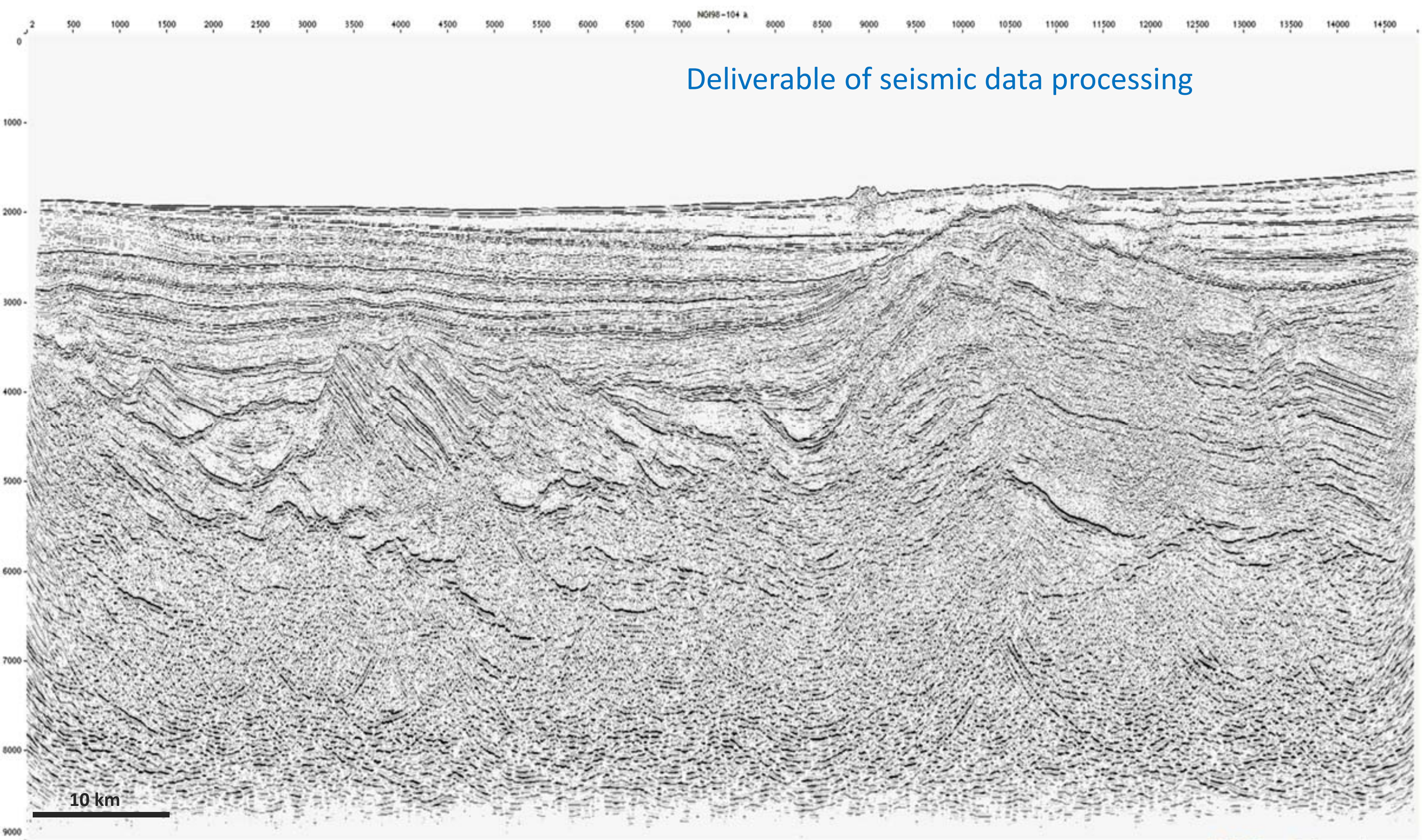
Seismic data to build structural map
(Fault / Surface)
after conventional interpretation

Seismic data to populate models
(e.g. Porosity, Lithology, Fractures)
if information is available

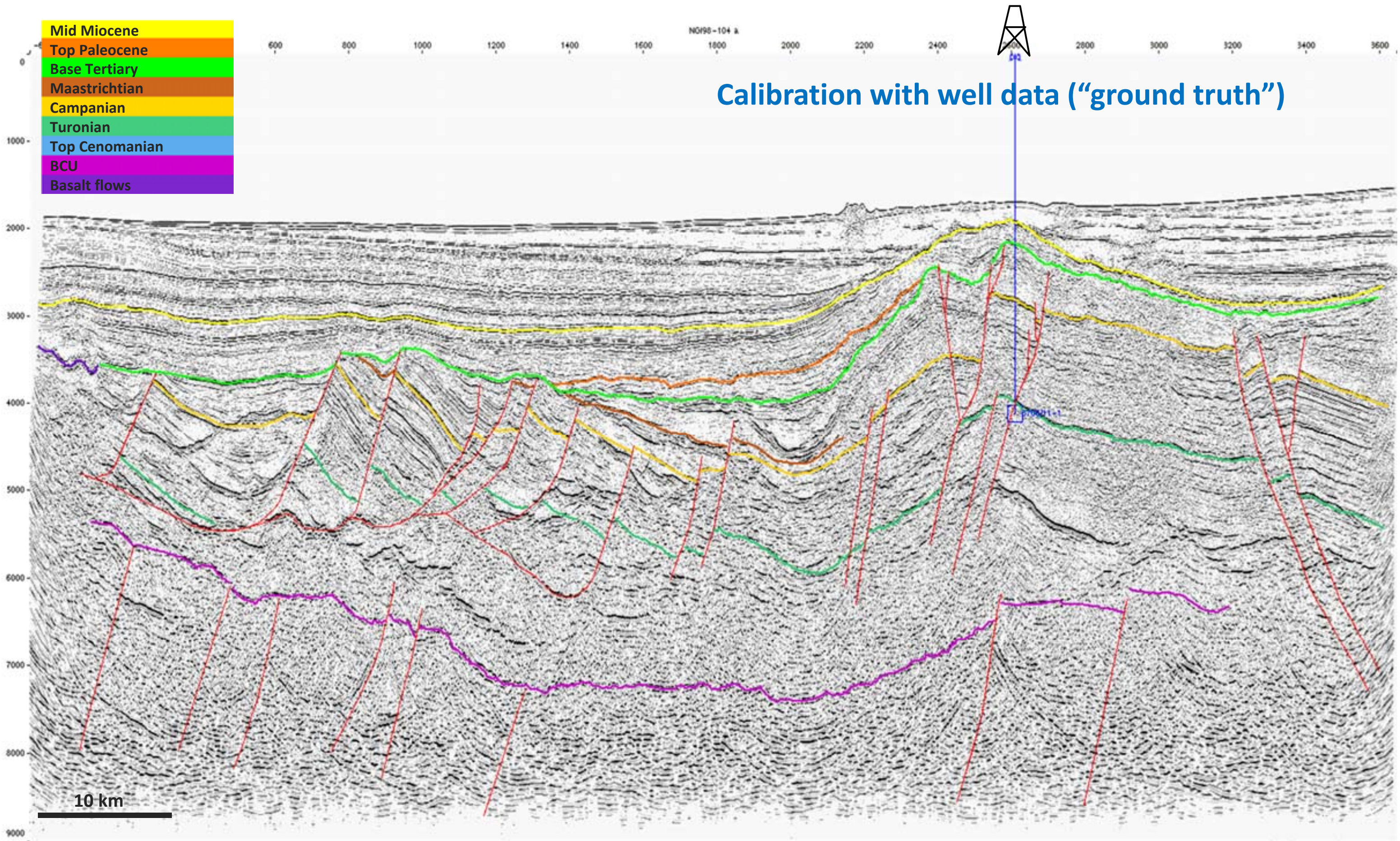
Part A: Trap geometry definition

Structural information

Seismic section - Raw

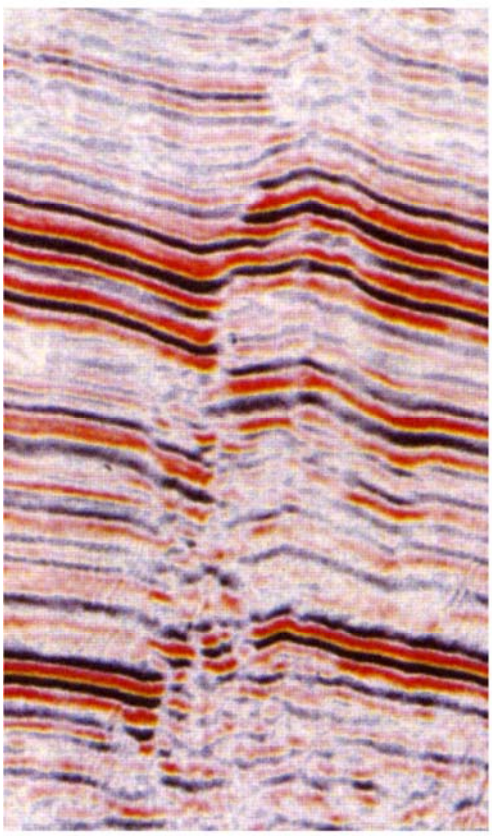


Seismic section - Interpreted

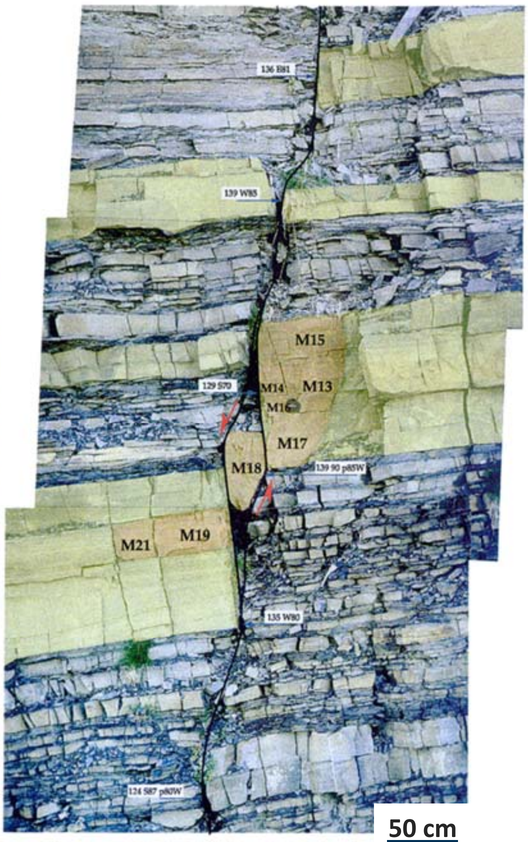


Picking faults on seismic

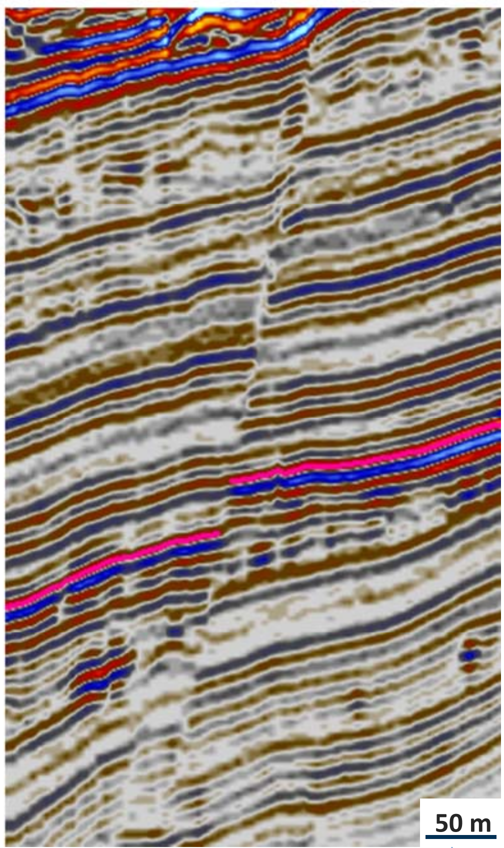
Seismic scale



Outcrop scale

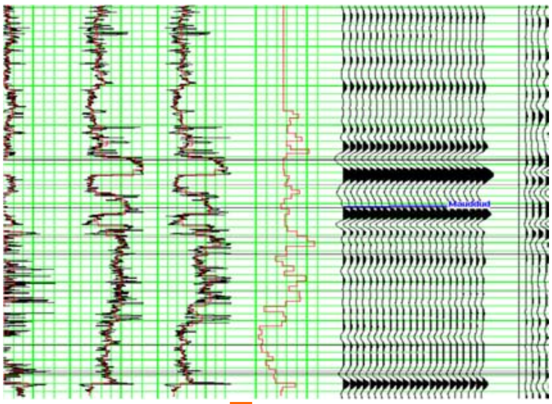


HR seismic scale

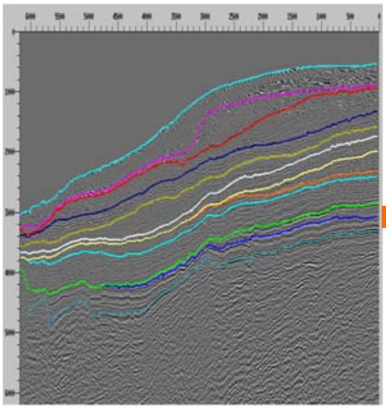


Time-to-depth conversion

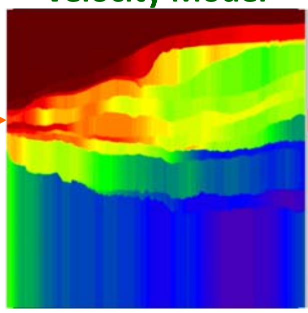
Well logs Synthetic seismogram



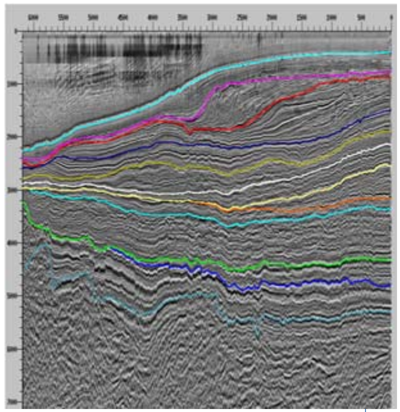
TIME



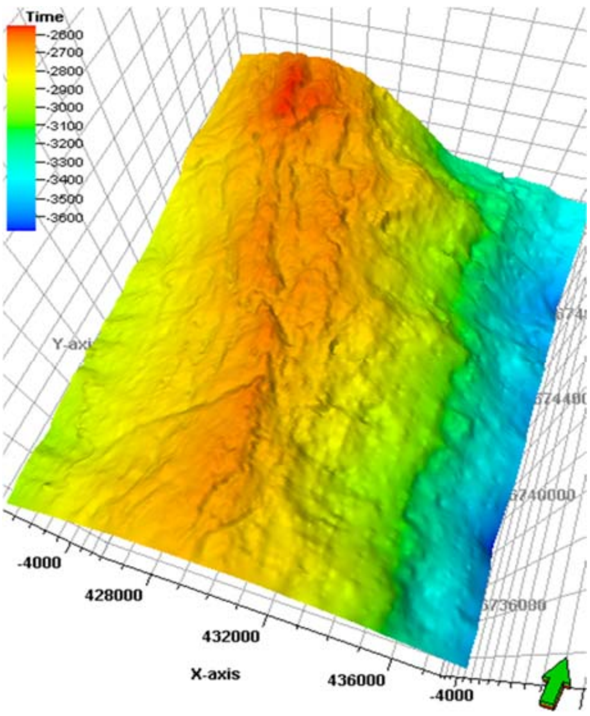
Velocity Model

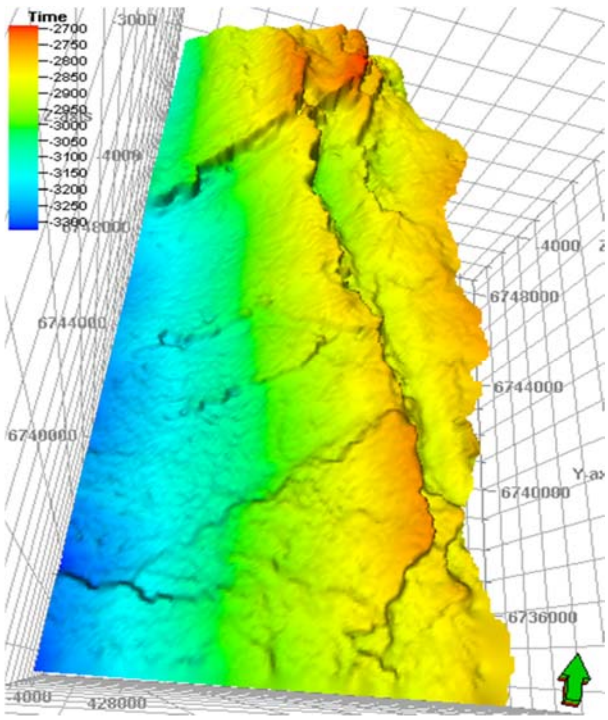


DEPTH



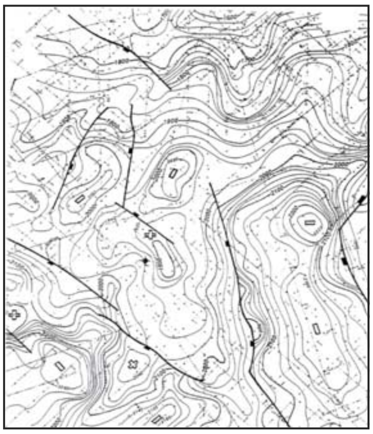
3D Structural Modeling (Time)





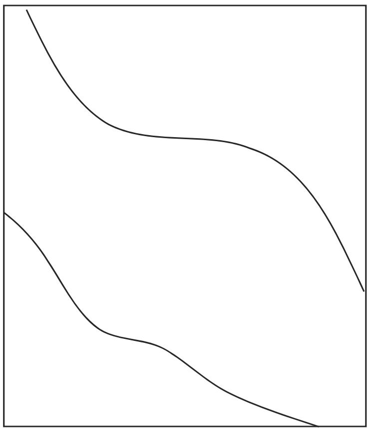
Time-to-depth conversion *Extract 3D structural information from*

Time-to-Depth conversion



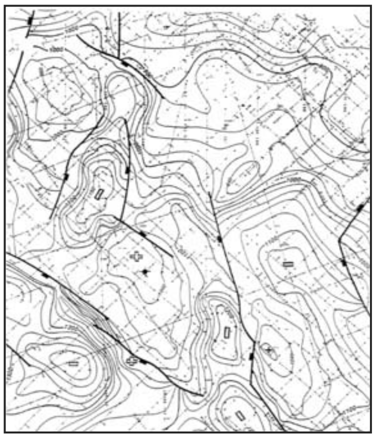
Depth map
(in m)

=



Velocity map

x



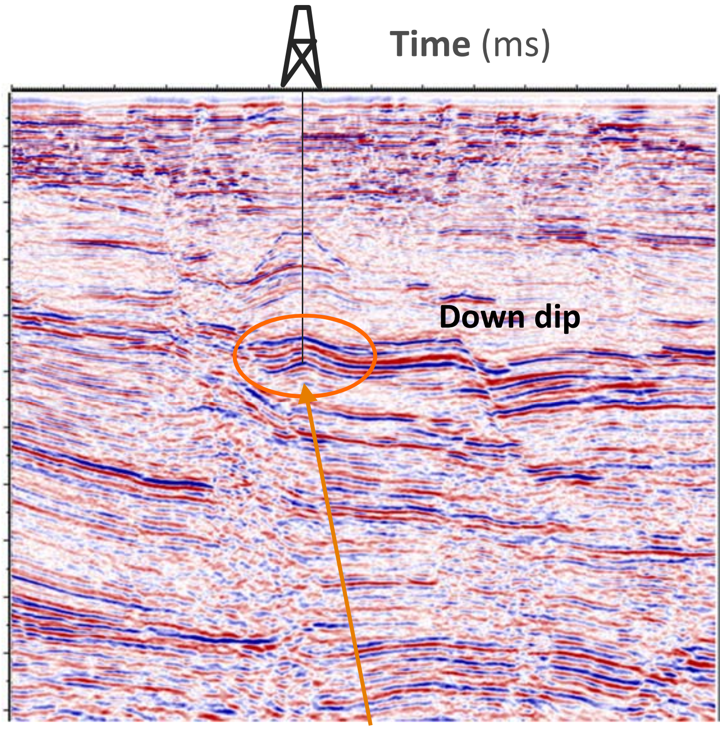
Two-Way Time map
(in sec.)

Depth map = (Velocity map /1000) **x (TWT map** /2)

→ sec to msec → 1 way time

Time-to-depth conversion example

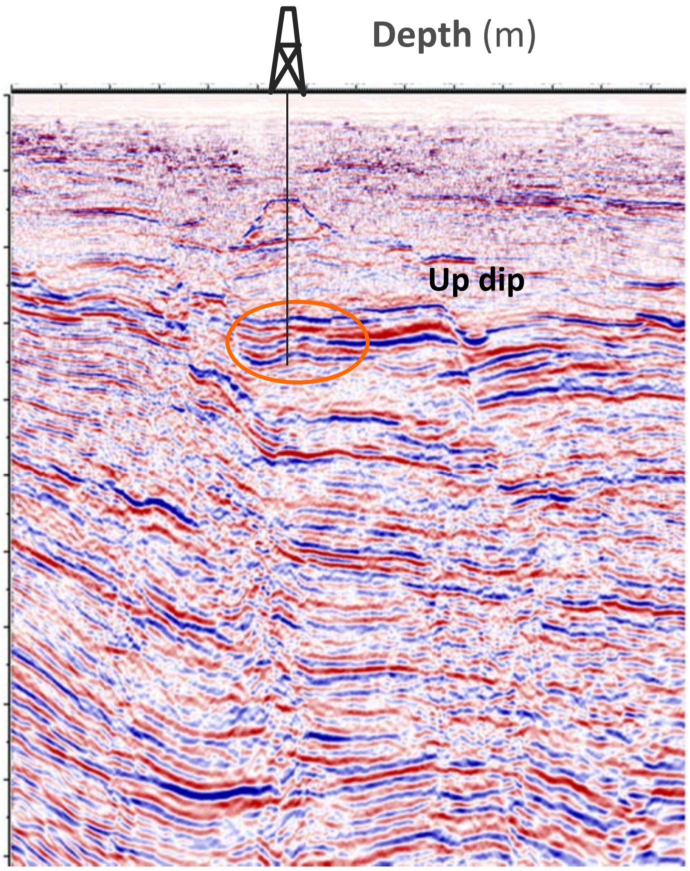
Time (ms)



Possible drilling location ?

Depth = Velocity x Time

Depth (m)

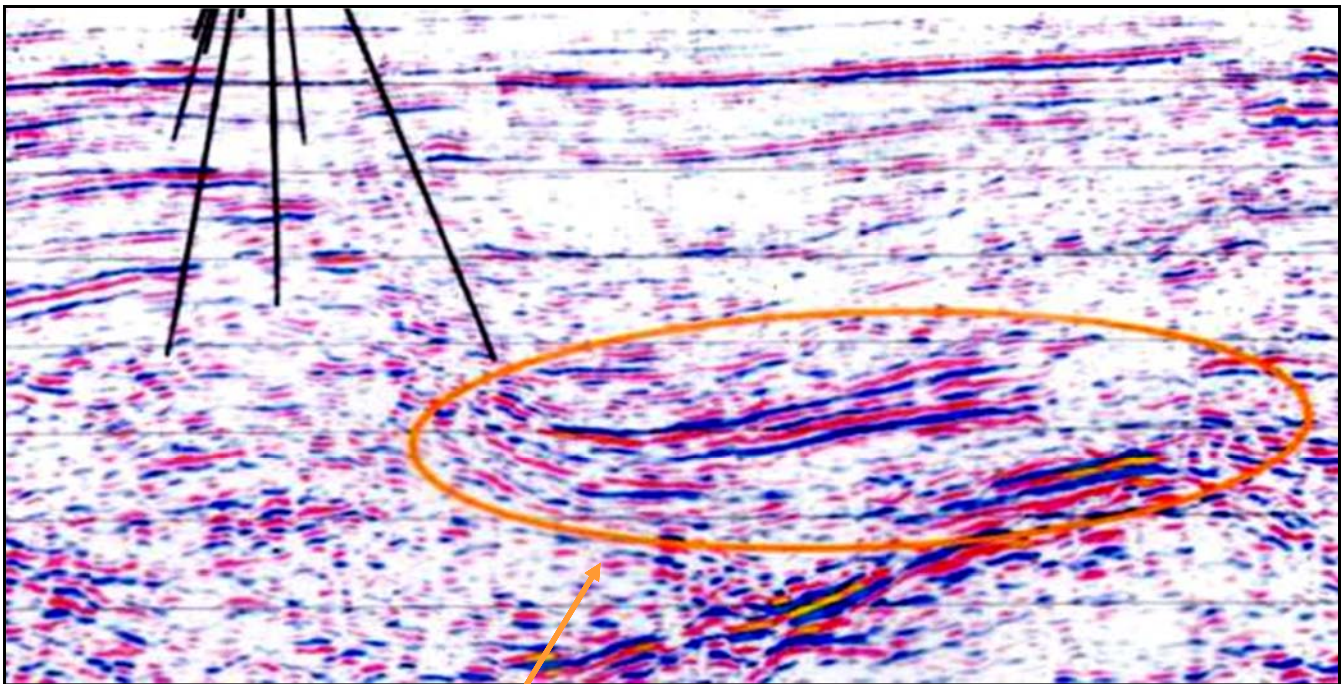


Would you still drill at the same location???

Part B: Extract information about the reservoir

Extract information on the reservoir

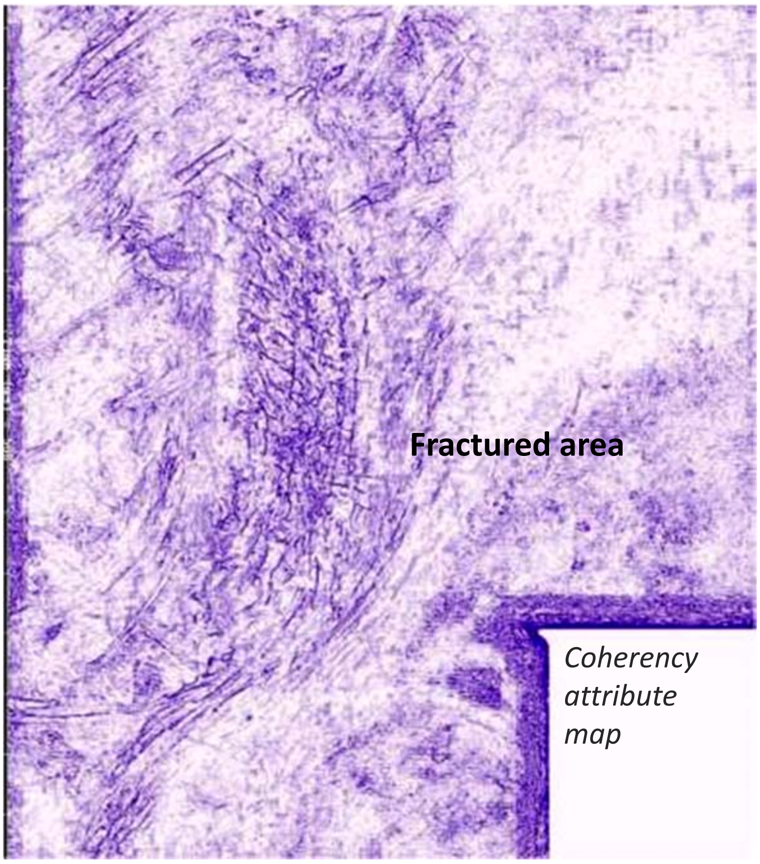
Detecting amplitude anomalies on seismic sections

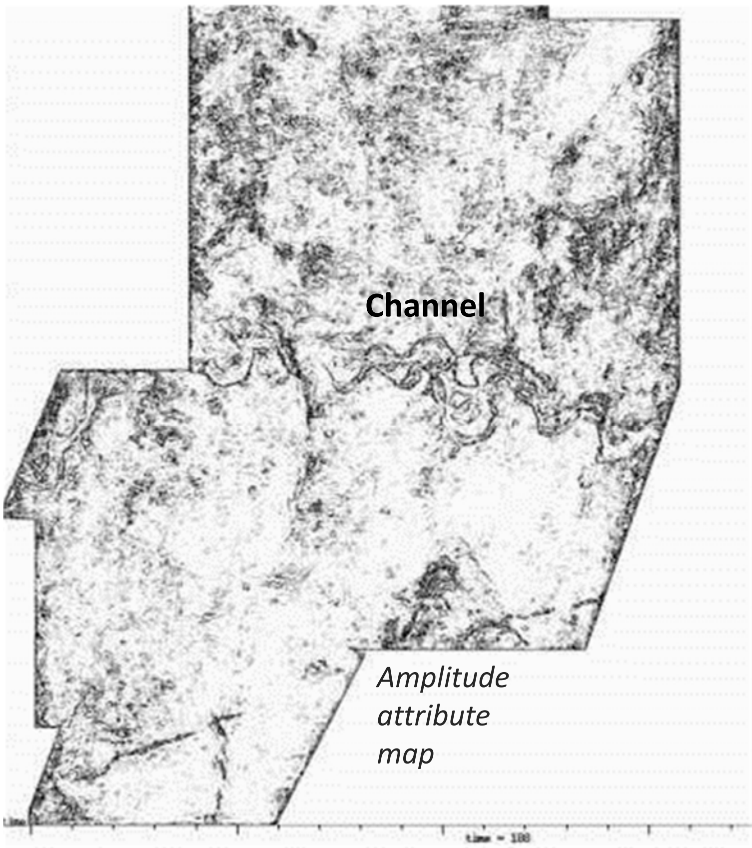


High amplitude underlying channel deposition

Get information about subsurface

Fractures - Sedimentary bodies

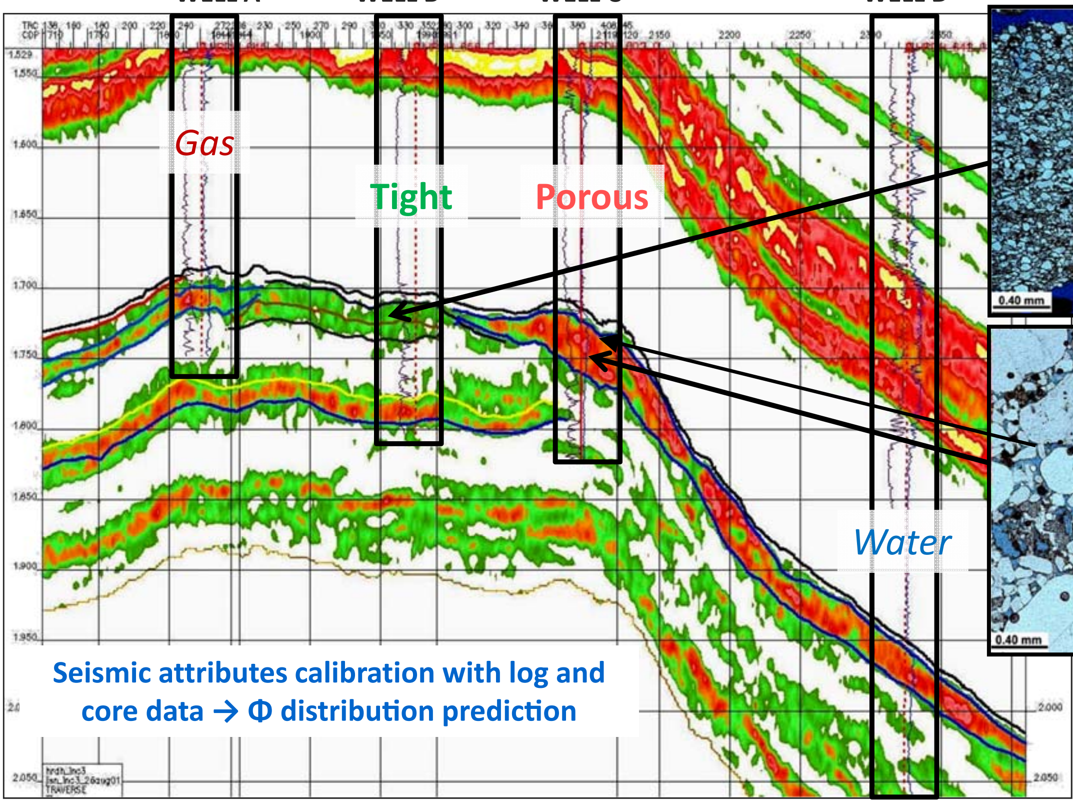


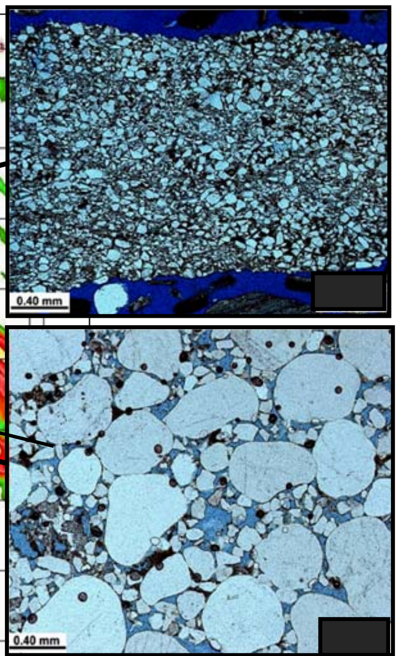


Get information about subsurface

Lithology, porosity or fluid content

Porosity detection through seismic inversion





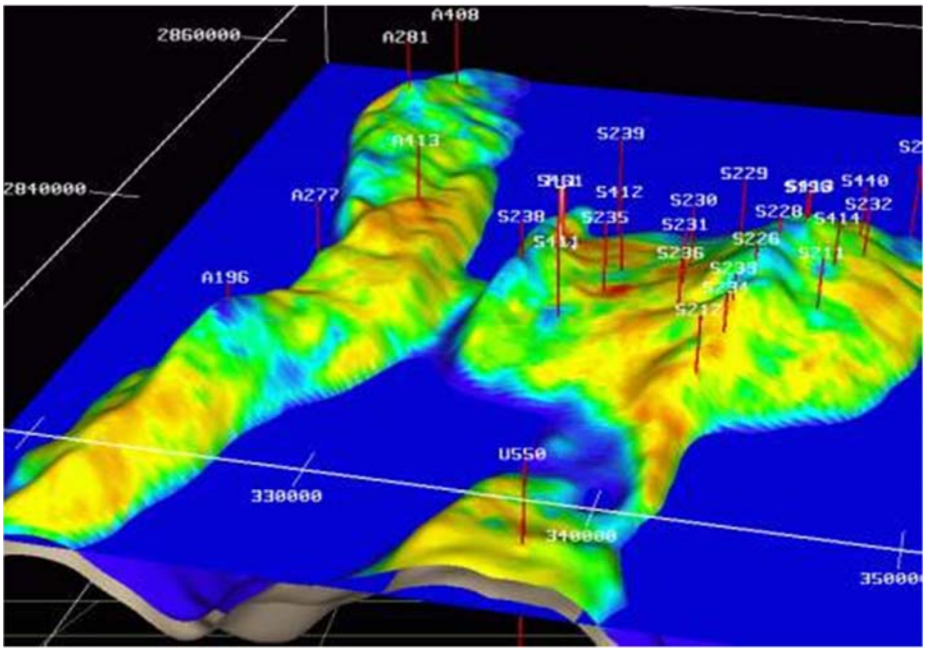
Impedance:
Higher (tight → Φ = 0)
Lower (gas → Φ = 15%)

Impedance cannot discriminate between gas-bearing reservoir and water-bearing reservoir

Get information about subsurface

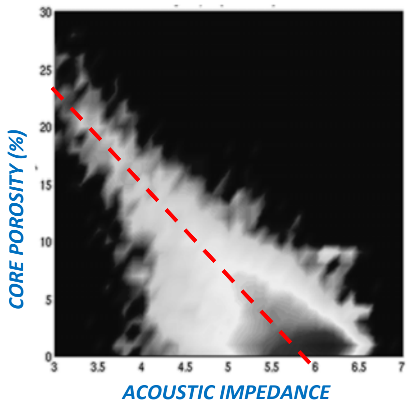
Porosity from attributes

Acoustic impedance vs porosity in carbonate reservoir

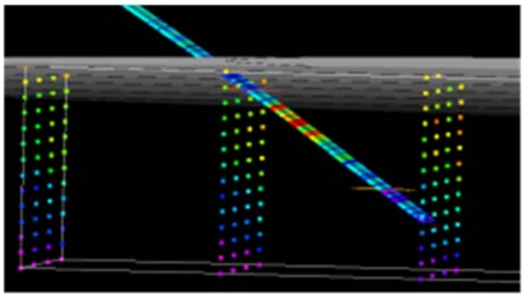


3D geostatistical distribution of reservoir porosity

→ Optimized positioning of future development wells



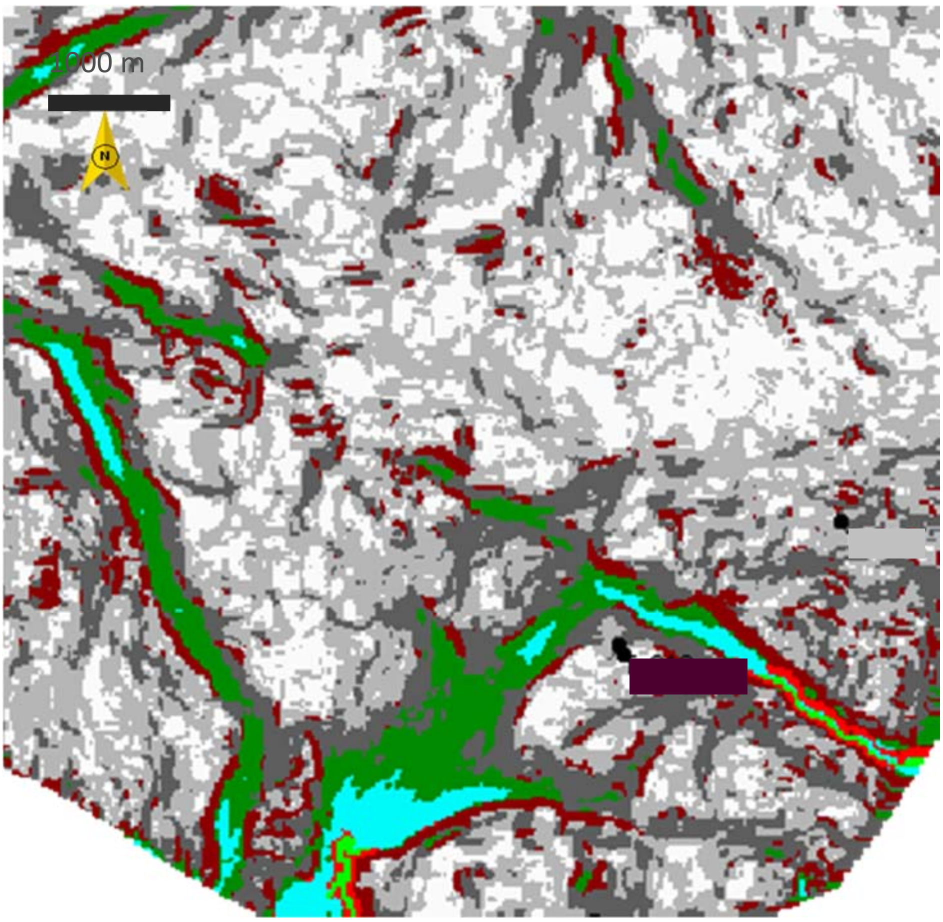
Seismic calibration with core information



Predicted porosity distribution along planned well path

Seismic facies analysis

Fracture density map based on seismic facies

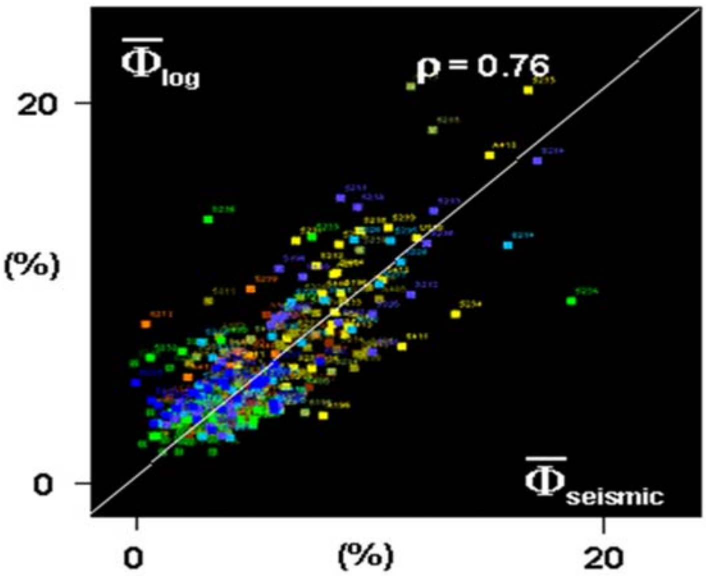


High	1
High	2
High	3
Medium	4
Medium	5
Low	6
Very low	7
Nil	8

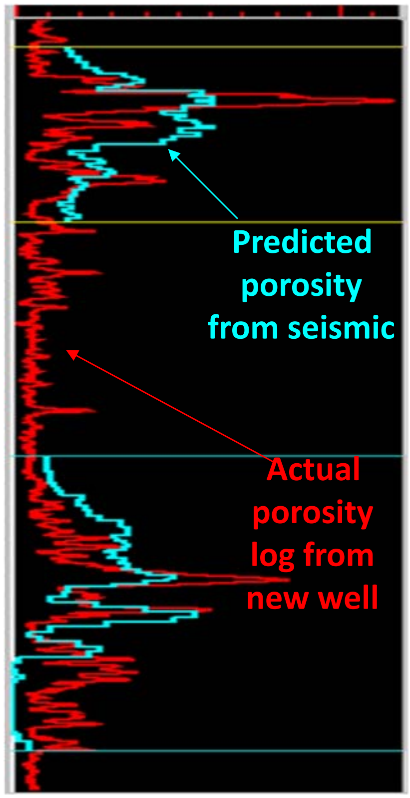
Get information about subsurface

Lithology, porosity or fluid content from attributes

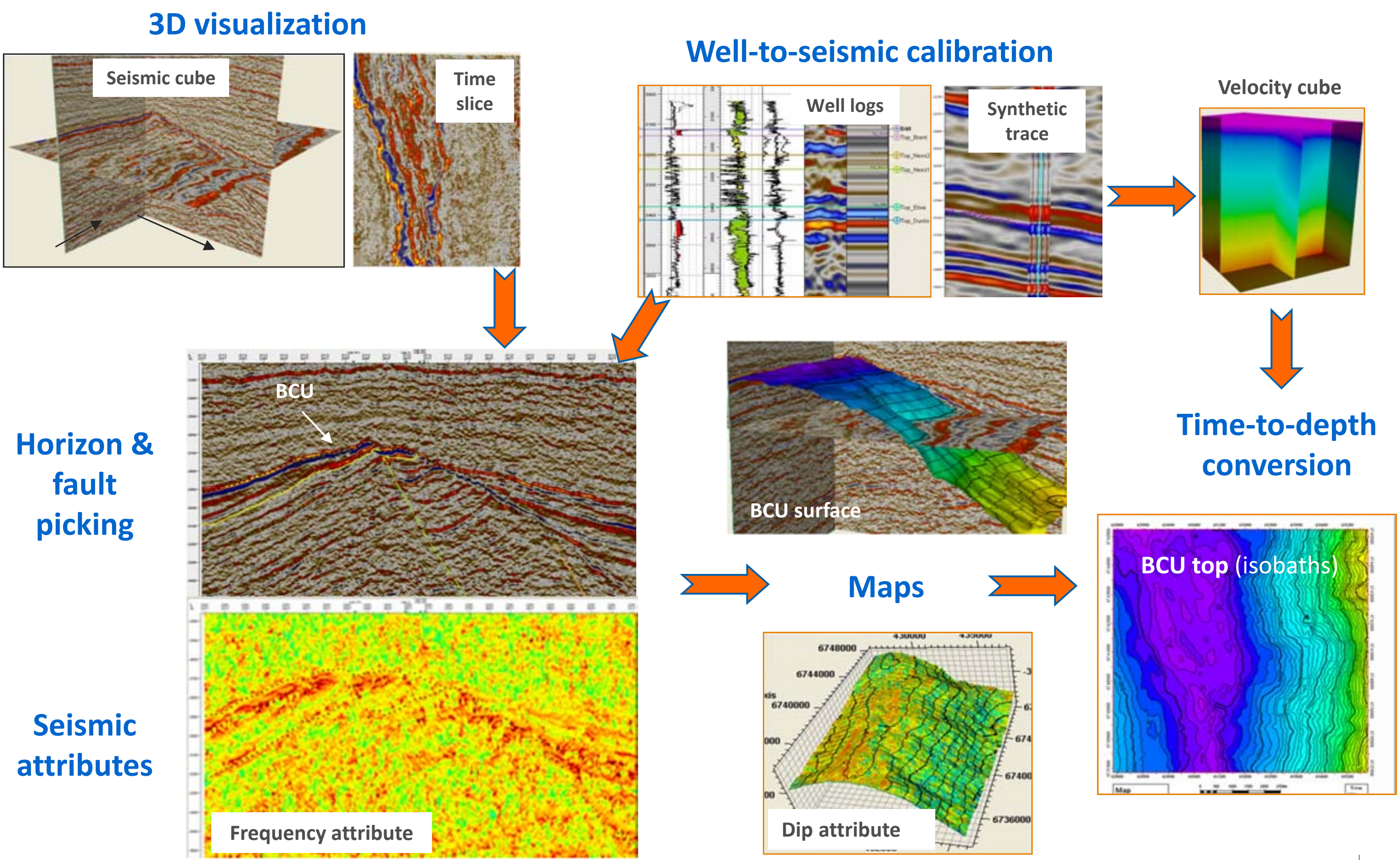
Porosity prediction



Zone-averaged porosities from log data and seismic (from inversion impedance)



Summary: seismic data interpretation workflow – 2/2



Seismic interpretation - Best advice

- **Before starting seismic interpretation, classify your objectives.**
  - When you interpret faults, start with main faults only to understand field architecture
  - Pick secondary faults afterwards
  - Use attributes to identify lineaments
- **Correlate your seismic interpretation with both well & dynamic data**
- **Use an attribute map not to pick main faults but to determine lineament network (such as sub-seismic faults) or any relationship with lithology or rock petrophysical characteristics.**
- **Simultaneous interpretation & analysis of several attributes allow to:**
  - Better define structure reservoir and properties
  - Better characterize reservoir
  - Minimize risk by robust analysis of uncertainties
- **Seismic resolution is scale dependent**

  → **seismic uncertainties are also scale dependent!**

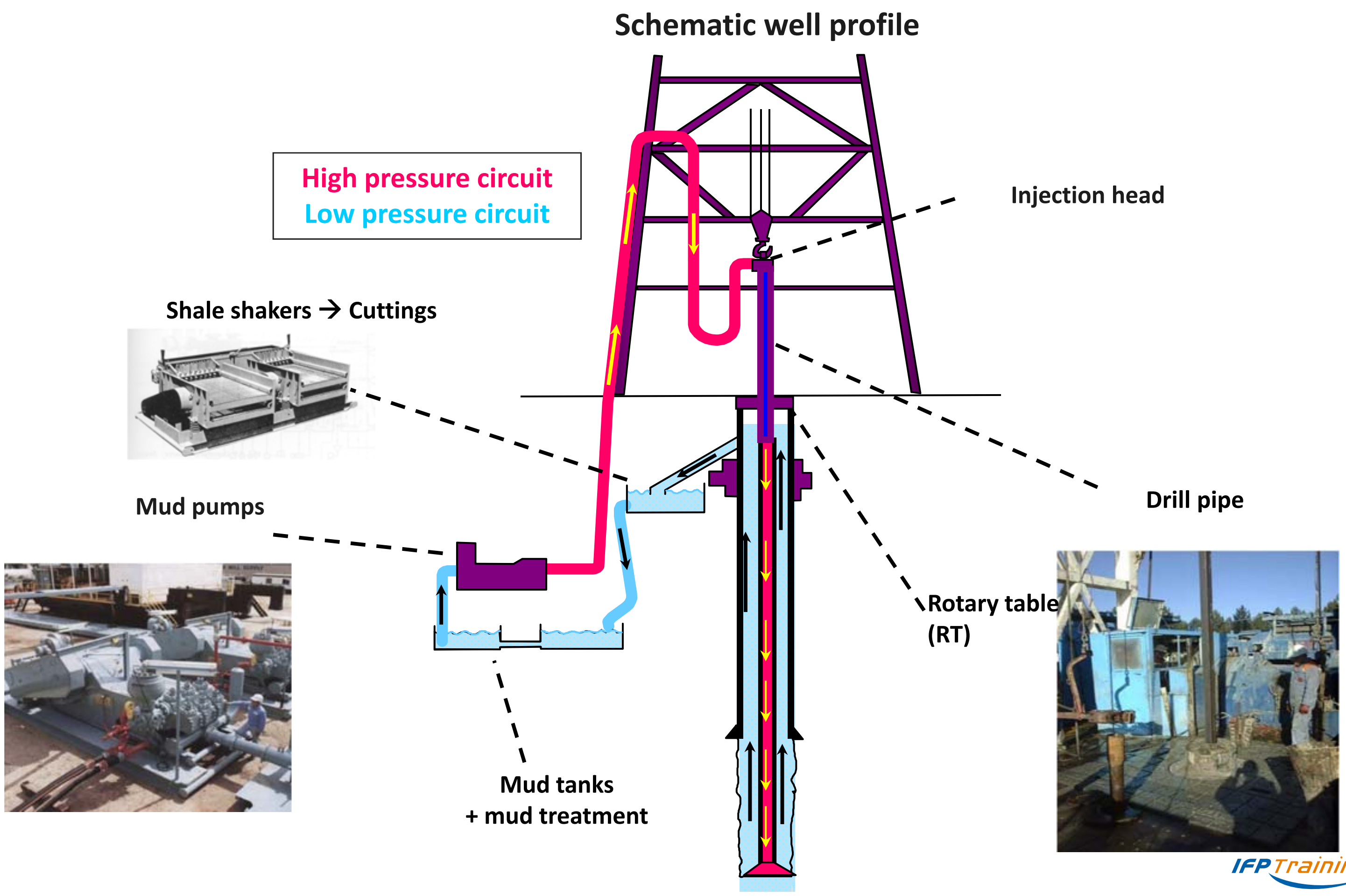
7. Qualitative well log interpretation

The "Quick-Look" method

Wireline logging

- Recording of **physical phenomena** linked with **petrophysical characteristics** of drilled **formations** and **fluids** in place.
- Recording **after the drilling** phase, every 15 cm down to 3 cm (1 foot > 1 inch)
- Logs provide a **continuous image of the subsurface** (*in situ*) detailed information but **limited to the wellbore** neighborhood (< 1 m diameter around the hole)
- **Three types of logs:**
  - Well logs for geologists: formation & fluid evaluation and characterization & quantification
  - Well logs for drillers: technical information (e.g. cementation quality, sticking point detection for fishing)
  - Well logs for production engineers: to analyze all phenomena linked to the fluids and their displacement

Mud & cuttings collection

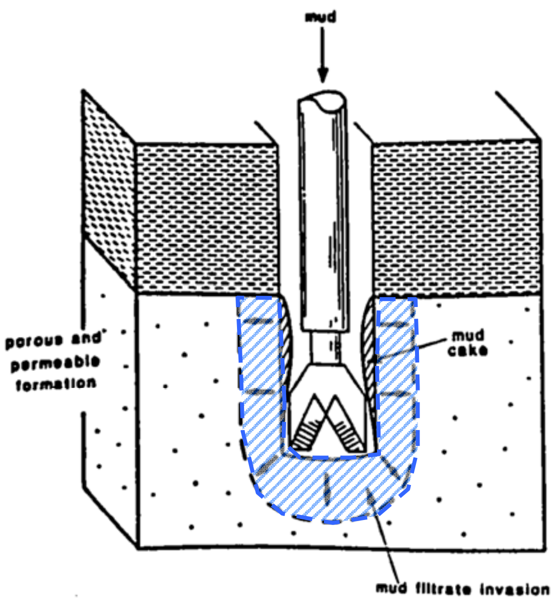


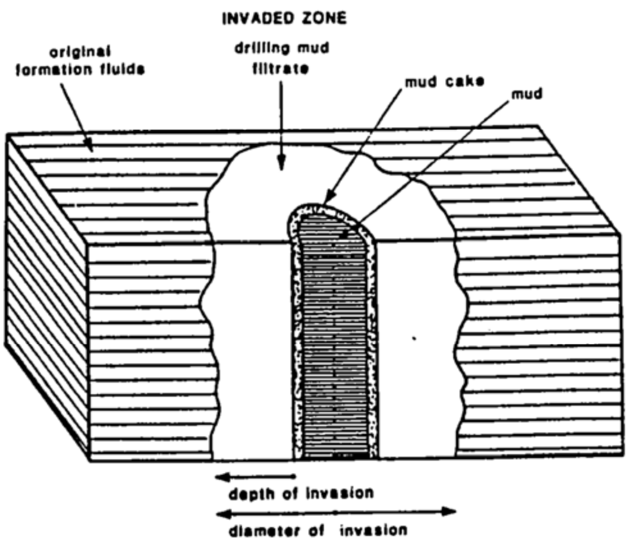
Drilling fluid characteristics

- **Multiple roles of the "mud"**
  - Clean the well
  - Keep cuttings in suspension
  - Lubricate the bit
  - Maintain the walls of the well
  - Prevent eruption (kick)
- **Characteristics of the mud**
  - Mud = fluid (water, oil) + solid particles
  - Dynamic equilibrium at well/formation interface
  - Mud Pressure > Formation Pressure
- **Phenomenon of invasion in reservoirs**
  - Invasion mud filtrate in the formation porosity network
  - Accumulation of particles in front of the reservoir → mud cake

Well logging: set up

Invasion





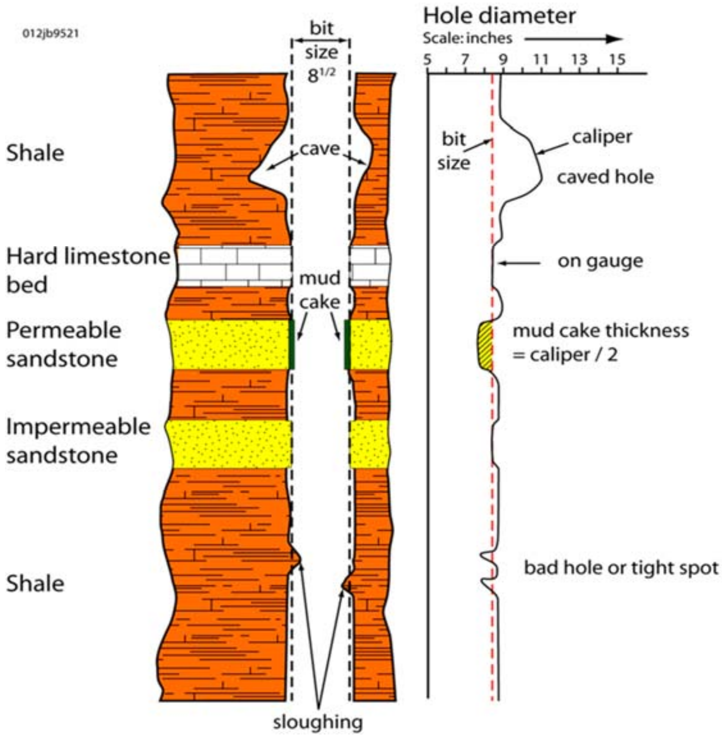
Wireline logging tools families and applications

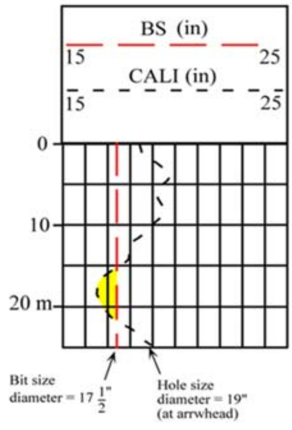
- **Recording of natural phenomena**
  - Wellbore diameter — Caliper
  - Natural radioactivity — Gamma Ray
  - Temperature of the formations — Temperature
- **Recording of properties after stimulation**
  - Formation resistivity — Resistivity & Induction tools
  - Lithology & porosity of the formations — Neutron, Density, Sonic
- **Tools**
  - Transmitter/receiver, with calibrated spacing provides
    - Depth of investigation
    - Vertical resolution
  - Centered in the borehole or mounted on a pad
- **Investigation of reservoir intervals and fluid content**
  - Reservoir identification (invasion phenomenon)
  - Fluid identification and relative saturations

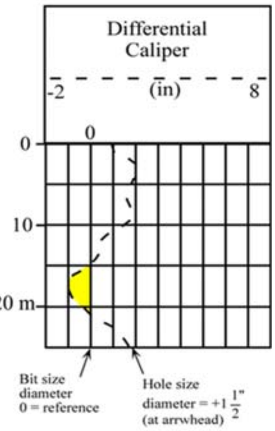
Caliper

- **Measures the borehole effective diameter**
  - Two opposites arms
  - Four arms, two by two in diagonal
- **Measurement in constant drilling phase**
  - Comparison with bit size
  - Fluctuates around bit size values
- **Applications**
  - Potential Mud cake location
  - Caves, irregularities in borehole walls

Caliper results



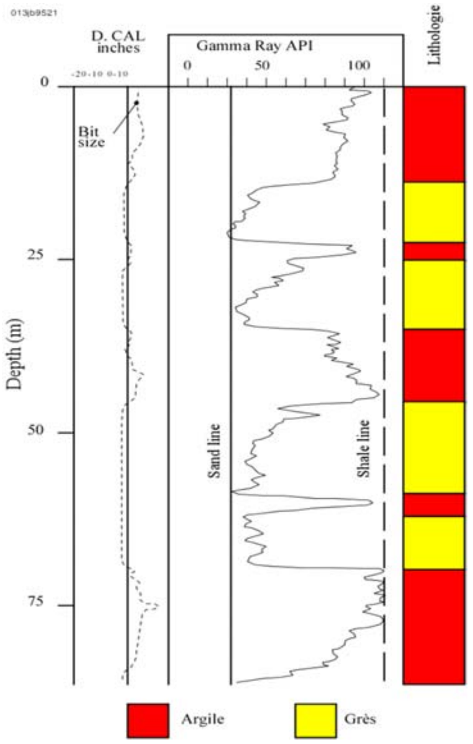


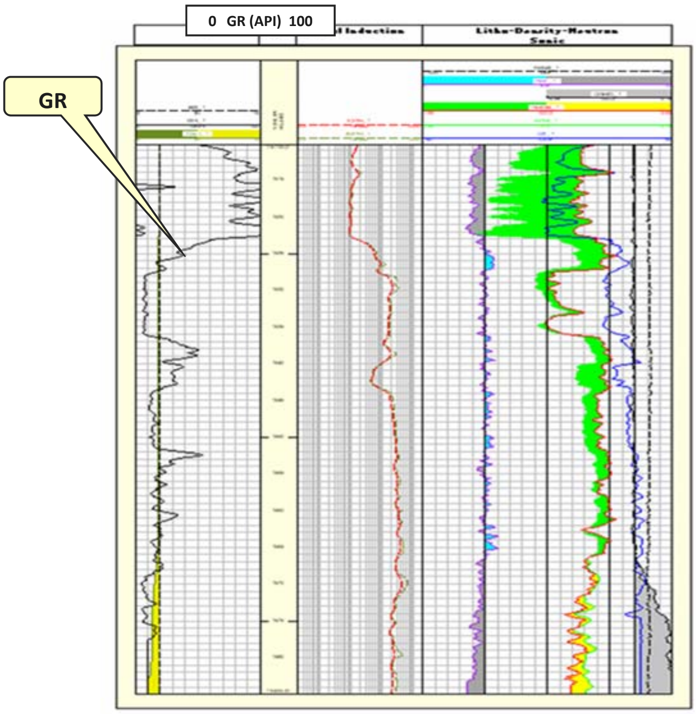


Gamma Ray

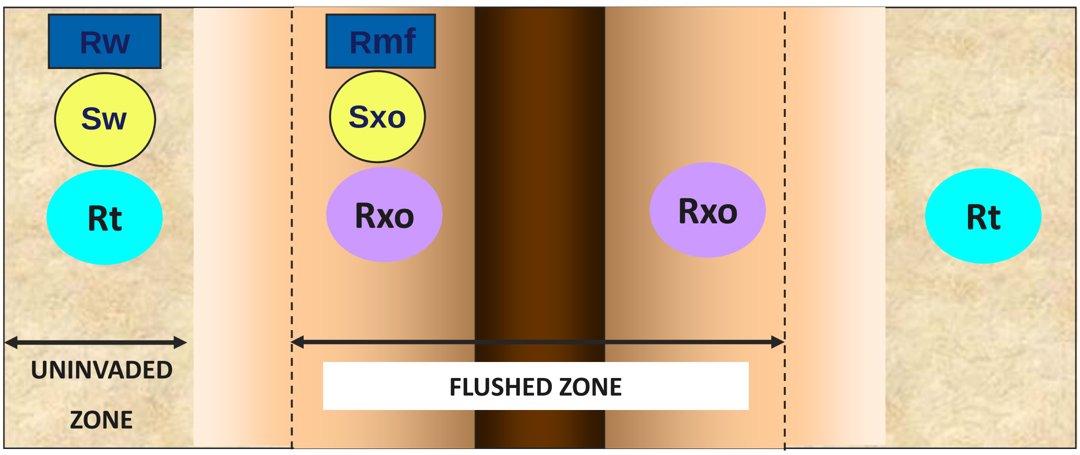
- **Measures the natural radioactivity in rocks**
  - Radioactive elements : Thorium, Potassium, Uranium
  - Global GR or Spectral GR
- **Representation on log**
  - API unit : from 0 to 100 or 150
  - Recording on first track, linear scale
  - Increasing on the right
- **Applications**
  - Shales layers, shales content in reservoir
  - Correlation between wells,
  - Sedimentary bed boundaries …

Example of GR log





Resistivity tool



Rmf = Resistivity of Mud filtrate

Rw = Resistivity of water in uninvaded zone,

Rxo = Global Resistivity of flushed zone,

Rt = Global Resistivity of uninvaded zone,

Sw = Saturation in water,

Sxo = Saturation of fluid in flushed zone

Archie Law – Formation factor

- This Global Resistivity Ro is proportional to the resistivity of water Rw

$$R_o = F R_w \qquad \textbf{with} \qquad F = \frac{a}{\phi^m}$$

$$R_{o1} = F R_{w1}$$

$$R_{o2} = F R_{w2}$$

$$\boxed{R_o = \frac{a}{\phi^m} \times R_w}$$

- The proportionality factor F is called the Formation Resistivity Factor and therefore it is the Ratio of Global Resistivity Ro to water resistivity Rw

Neutron tool

- **Measures the number of hydrogen nuclei in the formation**
  - Not located in the “conventional matrix” for reservoir
    - Sandstone, Limestone, Dolomite
  - Associated with fluids in porosity for reservoir formations
  - Gives an “apparent porosity”
- **Representation on log**
  - porosity unit : from 0 to 60 or -15 to + 45
  - Recording on linear scale
  - Increasing on the left
- **Applications**
  - Fluid content
  - Shale volume
  - Computation of porosity (true porosity in reservoir formation)

Density tool

- **Measures the global density of a formation**
  - Compton effect (attenuation of gamma rays in formations)
  - Gives an “apparent porosity”
- **Representation on log**
  - density unit : g/cc
  - Recording on linear scale
  - Increasing on the right
- **Applications**
  - Fluid content
  - Shale volume
  - Computation of porosity (true porosity in reservoir formation)

Sonic tool

- **Measures propagation of acoustic waves in the formation**
  - Seismic refraction
  - Time delay in the formation between a reference spacing (Δt)
  - Gives Interval Velocities
- **Representation on log**
  - unit : microsecond/feet
  - Recording on third track, linear scale
  - Increasing on the right
- **Applications**
  - Identification of lithologies
  - Computation of porosity (true porosity in reservoir formation)
  - Secondary porosity

Main logging tools

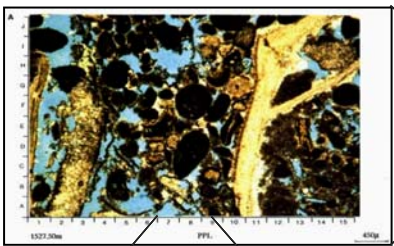
	Measured phenomena (borehole, formation or fluid)	Depth of investigation	Vertical resolution	**Application**
Caliper	**Well-bore diameter**	none	1,3 cm	Identification of **mud cake**, i.e. presence of a **reservoir**
GR	**Natural radioactivity**	30 cm	30 cm	Identification of **shaly formations** (seals)
Resistivity	**Resistivity and conductivity of formations (rocks & fluids)**	3 cm to 2 m	10 cm to 1 m	Identification of **fluid types** Measurement of **hydrocarbon saturation**
Neutron **Density** **Sonic**	▪ **Emission of neutrons** ▪ **Emission of gamma rays** ▪ **Travel time of acoustic waves**	12 to 25 cm ~10 cm 1 to 12 cm	40 to 60 cm 10 cm 60 cm	Formation's **lithology** Reservoir's **porosity**

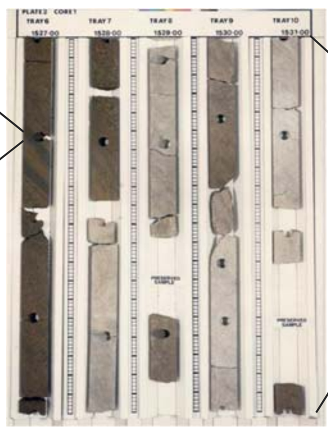
Well data: scales of observation

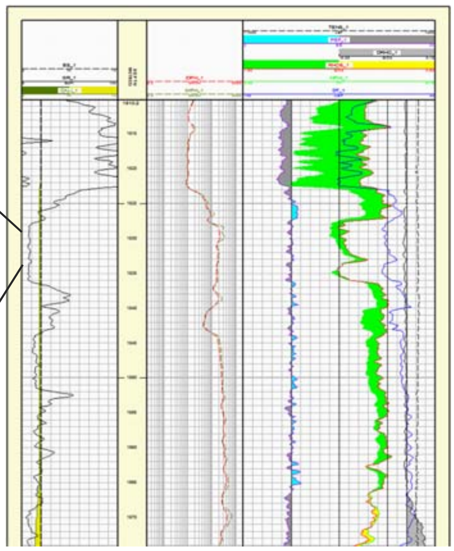
Thin section
µicron → mm

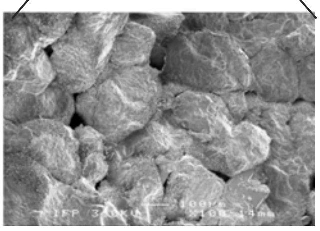
Core
mm → dm

Log
dm → m









Scanning Electron Microscope
µicron

Quick-look qualitative log interpretation - Objectives

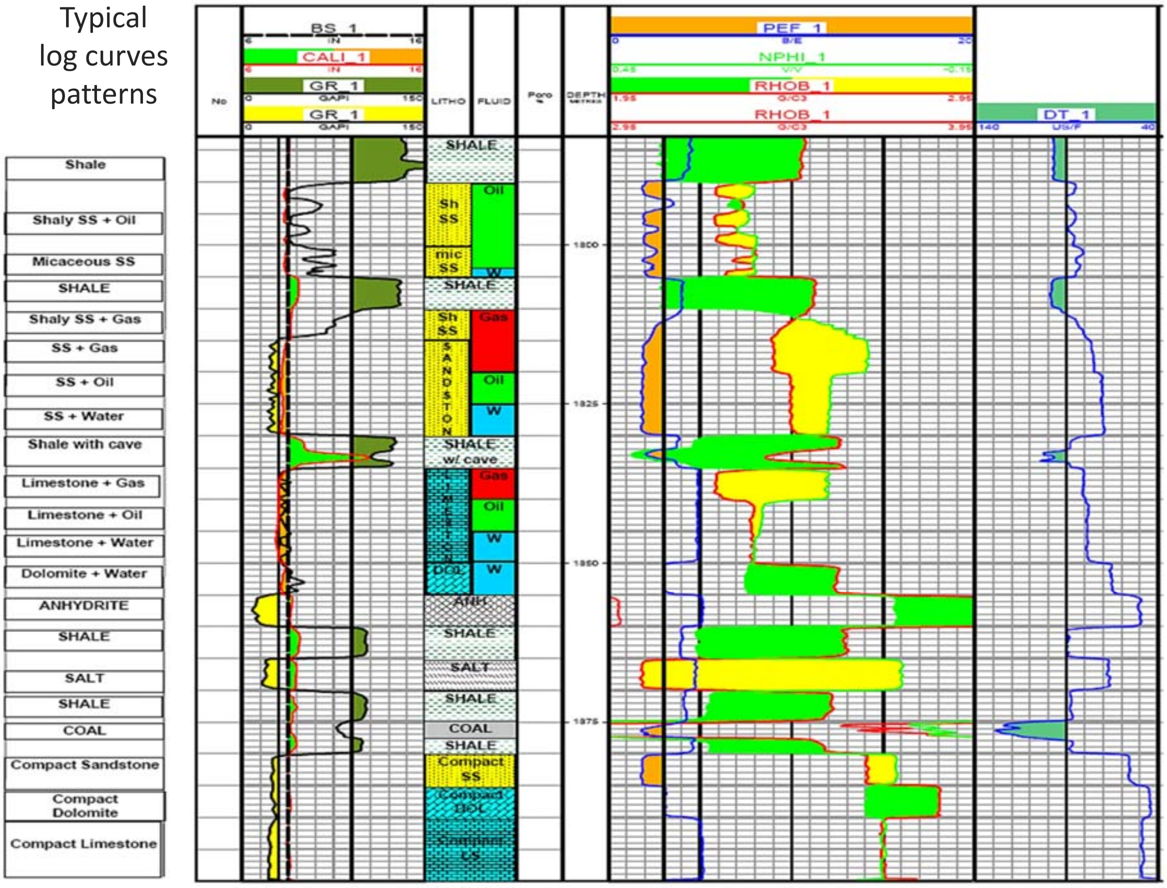
- Delineation of reservoirs
- Identification of non-reservoir zones
- Identification of fluids in reservoir
- Identification of fluid contacts in HC-bearing zones
- Determination of formation water resistivity (Rw)
- Estimation of both water and hydrocarbon saturations in HC zones
- Determination of lithology and porosity in reservoir zones
- Estimation of OOIP at the well.

Well log interpretation

- **Logging records allow the collection of detailed data around the well**
  - Combination of proximal and distal data
  - Identification of successive lithologies in the borehole
- **Interpretation of well logging records**
  - Identification of the reservoir formation
  - Identification of the fluid content (water, oil, gas)
  - Computation of porosity, and fluid saturation
  - Comparison with laboratory's data (petrophysics)
- **Correlation between wells**
  - Correlation of key surface through the basin
  - Combination with seismic data (well tying)

Typical log responses in common geological formations

Typical log curves patterns



Average quick-look values for common lithologies

Average corresponding log values

Lithology	Zone W/O/G	Temp C	Rmf	SSP mV	ZONE	GR API	RHOB g/c3	NPHI %	PEF	DT us/ft	Poro DN PHIDN %
		59				135	2,47	36	4,5	97	
Shale					W	37	2,25	21	2	85	
Shaly Sandstone	O	59			V	60	2,27	22	2	89	24%
Shaly Sandstone	O	59	0,176		U	45	2,27	21	2	85	25%
Micaceous SS	W				T	50	2,30	21	2	85	21%
Shale					S	130	2,30	36	4	100	24%
Shaly Sandstone	G				R	70	2,50	9	2,5	80	
Sandstone	G				Q	25	2,40	3	2	75	15%
Sandstone	O	60	0,176		P	25	2,40	9	2	70	12%
Sandstone	W				O	25	2,45	9	2	70	12%
Shale					N	110	2,40	40	2	100	
Limestone	G	60	0,2		M	30	2,25	9	5	80	23%
Limestone	O	60	0,2		L	30	2,35	20	5	80	21%
Limestone	W	60	0,2	-20	K	30	2,36	21	5	80	21%
Dolomite	W				J	45	2,57	22	3	65	15%
ANHYDRITE					I	13	2,97	-2	5	50	0%
Shale					H	100	2,60	30	4	90	
SALT		60	0,176		G	16	2,04	-3	5	67	0%
Shale					F	100	2,55	28	4	89	
COAL					E	75	1,57	54	2	129	
Compact Sandstone (Quartzite)					D	25	2,65	-2	2	56	0%
Compact Dolomite					C	27	2,85	3	3	44	0%
ompact Limestone					B	24	2,70	0	5	49	0%
ompact Limestone		61			A	24	2,70	0	5	49	0%

8. Reservoir characterization

Facies analysis

Clastic environments

Rocks: definitions

Three types of rocks on Earth:

- **Magmatic (igneous) rocks**
  Formed by cooling and crystallization of magmas:
  - slowly, at great depth: plutonic rocks (e.g. granites)
  - quickly, at shallow depth or surface: volcanic rocks (e.g. basalts)

- **Metamorphic rocks**
  - Formed by transformation of pre-existing rocks under elevated pressures and/or temperatures (e.g. schists, gneiss).
  - All these rocks are combinations of minerals (recrystallized).

- **Sedimentary rocks**
  Formed at the surface:
  - by **mechanical processes**, i.e. erosion of pre-existing rocks, transportation and deposition (e.g. sandstones, shales)
  - by **chemical / biochemical processes** (e.g. precipitation) followed by moderate depth burial (e.g. limestones)

Characteristics of sedimentary rocks

Sedimentary rocks:

- are the only formations that can **generate** and **accumulate hydrocarbons**
- form at the surface of the Earth, by accumulation of particles
- represent only 5% of the Earth's crust volume, **but cover 75% of its surface**
- generally deposit as successive **layers** (stratifications, beds)

Sedimentary rock characteristics:

- **Grains**
  - Mineralogy
  - Grain size, Grain shape (morphology)
  - Sorting
- **Pores** (void spaces)
  - Porosity (percentage of void volume > various types of porosity)
  - Effective porosity (interconnected voids)
  - Permeability (ability to allow a fluid to flow)
- **"Matrix"**
  - Matrix (primary binding material, deposited with grains)
  - Cement (secondary binding material, deposited after sedimentation, i.e. diagenetic)

➢ **Reservoir parameters !**

Clastics vs Carbonates

Siliciclastic rocks

- **Origin : Allochthonous sediments**
  - **Erosional product**
- **Transport : Rivers, wind**
  - **Short or long distance**
  - **Decrease of grain size**
- **Deposition**

  Basin (different from the original one)
  - **Dynamic of deposition : High energy or low energy**
  - **3 main families: Conglomerate , sandstone, shale**
  - **Quality of porosity and permeability**

Carbonate rocks

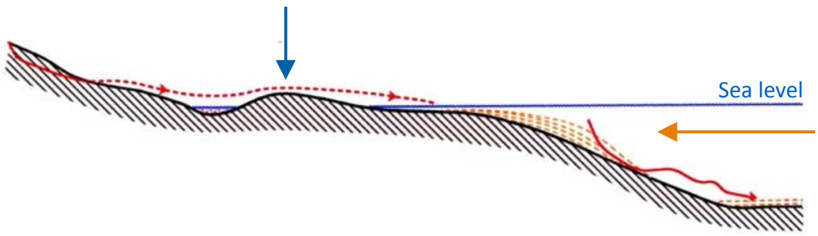
- **Origin : Autochthonous sediments**
  - **Growth in place (crystallization or precipitation)**
- **Transport : Generally absent or very short**
- **Deposition**

  Depositional area = medium of origin
  - **Dynamic of depositional**
    - ✓ **Limestone : Ca CO3**
    - ✓ **Dolomite : Ca C03, Mg**
- **Specificity**
  - **Strong influence of chemical transformation after deposition (diagenetic effects on Porosity and permeability**

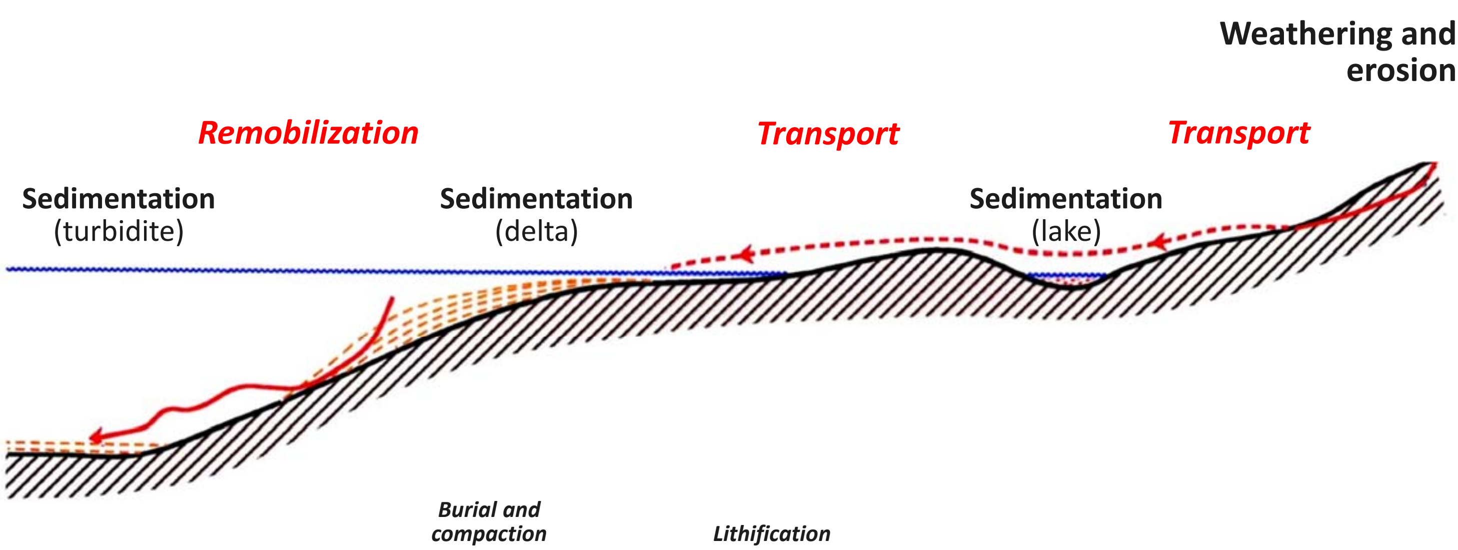
Sedimentary depositional environments

Continental environments
- **Glacial**
- **Aeolian**
- **Lacustrine**
- **Fluvial**
  - Braided
  - Meandering
  - Anastomosed
- **Coastal plain**

Marine environments
- **Shoreline** (coast/beach)
- **Delta**
  - Fluvial-dominated
  - Wave-dominated
  - Tide-dominated
- **Continental shelf**
  - Siliciclastic
  - Carbonatic
- **Slope, canyon**
- **Basin**
  - Turbiditic fan
  - Abyssal plain



Deposition of clastic sediments

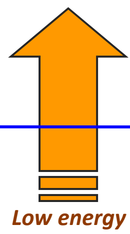


Final deposition → Diagenesis → Sedimentary rocks

Allochthonous sediments

Increasing depositional energy

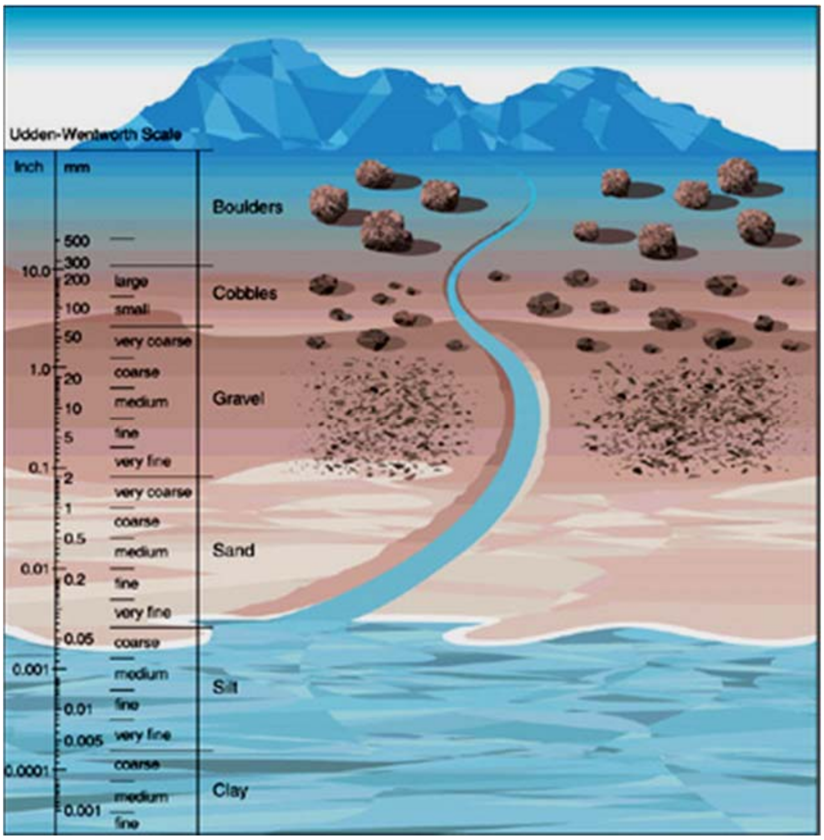
- **Conglomerates**
- **Sandstones**
- **Siltstones**
- **Shales**

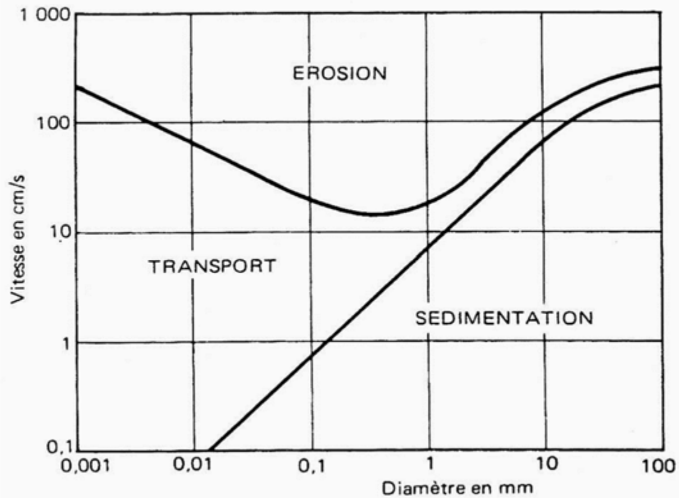


Potential reservoirs

Potential seals

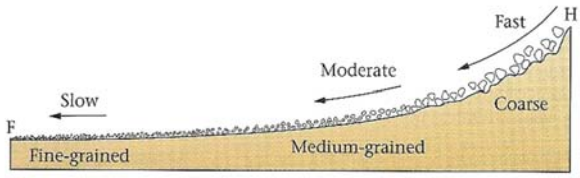
Clastic depositional processes





Hjulstrom's diagram:

Evolution of erosion vs deposition with stream (or current) speed and particle size, for soft sediments



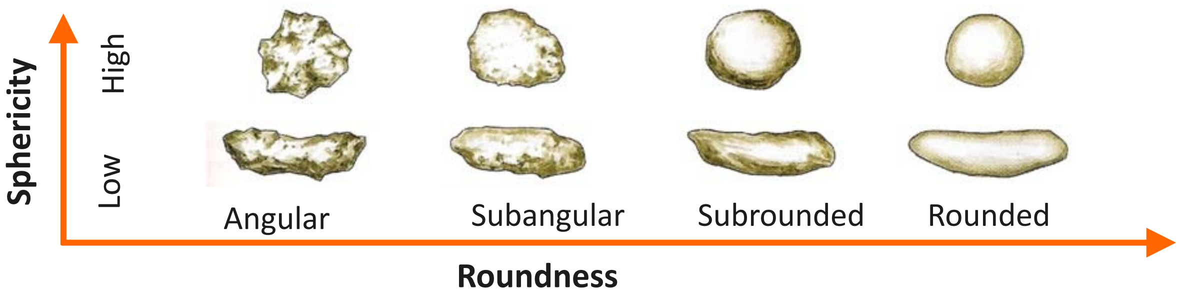
Description of sediments

Size, sorting & shape

- **Sorting**

- **Sorting** refers to the range of particle sizes in a sediment or sedimentary rock. In general, sediments which have travelled relatively long distances from their source are well sorted while those that have not travelled far are poorly sorted

- **Shape and roundness**



- **Roundness** refers to the roughness of the surface of the sedimentary grain. In general, grains become more rounded the further they are from their source rock
- **Sphericity** refers to the shape of the grain and is largely inherited from the host rock

Grain size classification

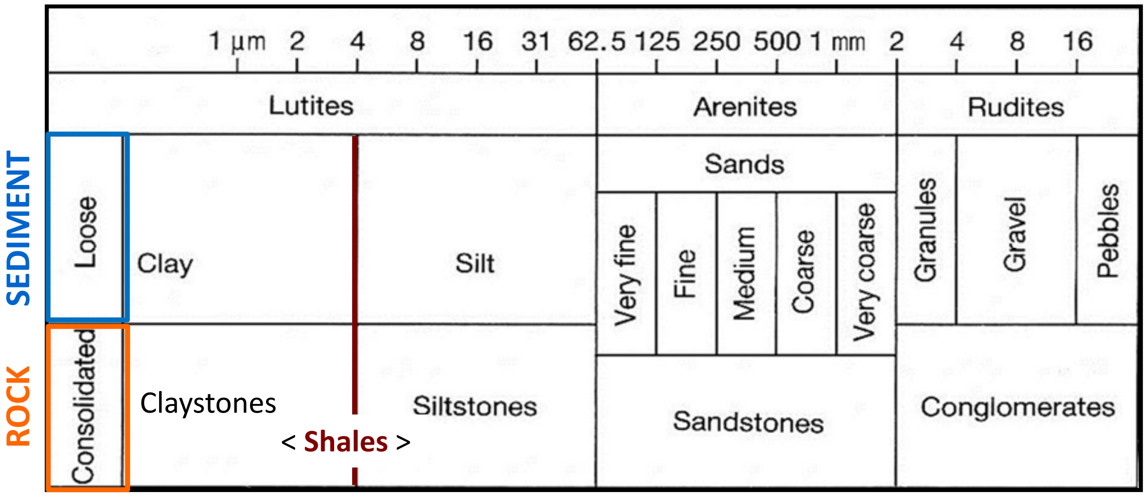
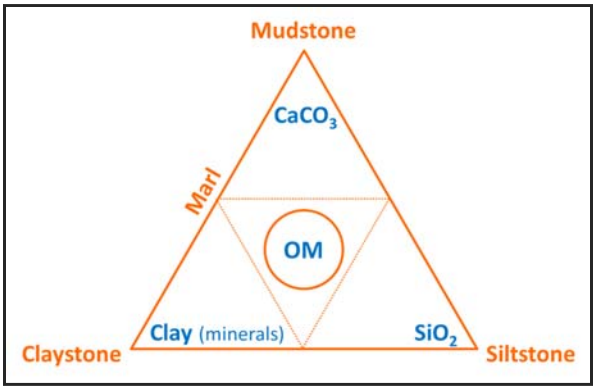


Table of clastic granulometric (grainsize) classes

Clastic rocks

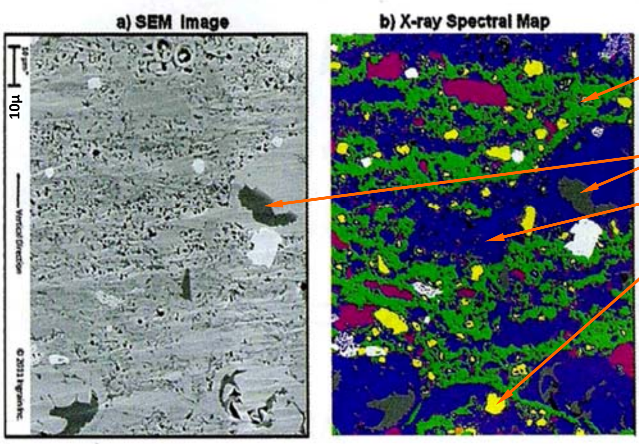
classification is complex because several variables are involved. Particle size (both average size and range of particles sizes), particles composition, cement and matrix type must all be taken into consideration



Shales

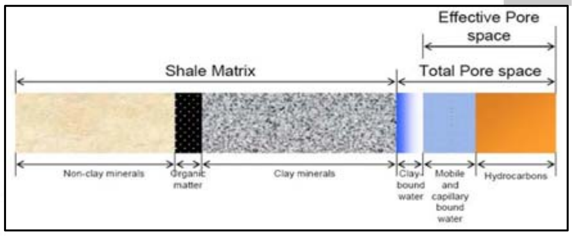
(mostly clay minerals) are generally further classified according to composition and bedding

Composition of a shale

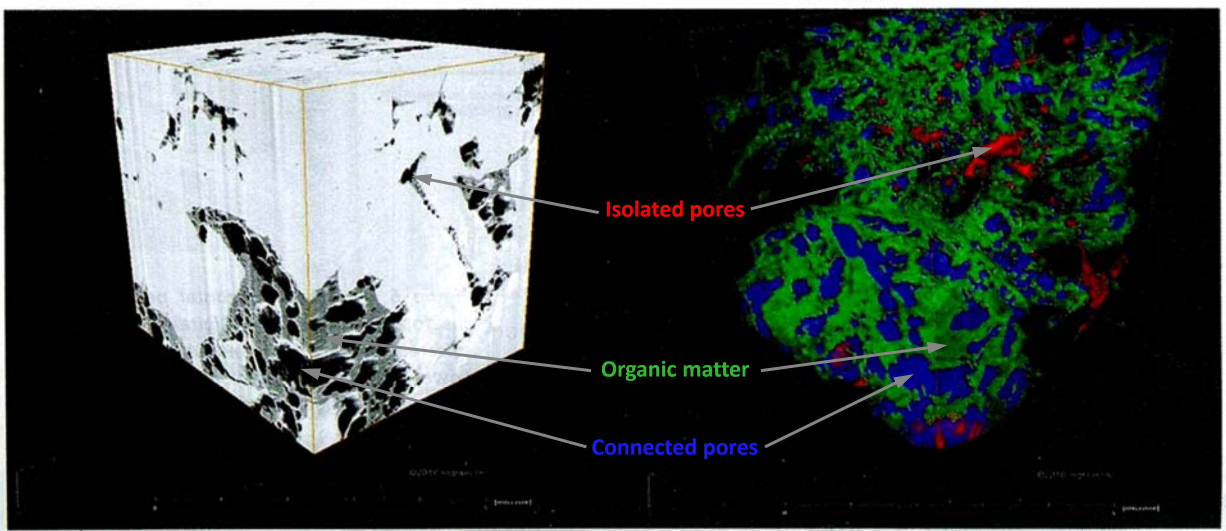


c) Mineral Distribution (% by vol)

clay	27.7
pore	1.7
organic	7.2
calcite	48.7 *
qtz	4.3
plagioclase	8.1
pyrite	2.2
TiO2	0.1
Total	100



Mineralogy by EDS obtained during Stage 2 analysis for a typical sample from Well B. Note how the clay minerals (in green) are distributed in roughly horizontal bands (up direction in image is same as up direction in original deposition).



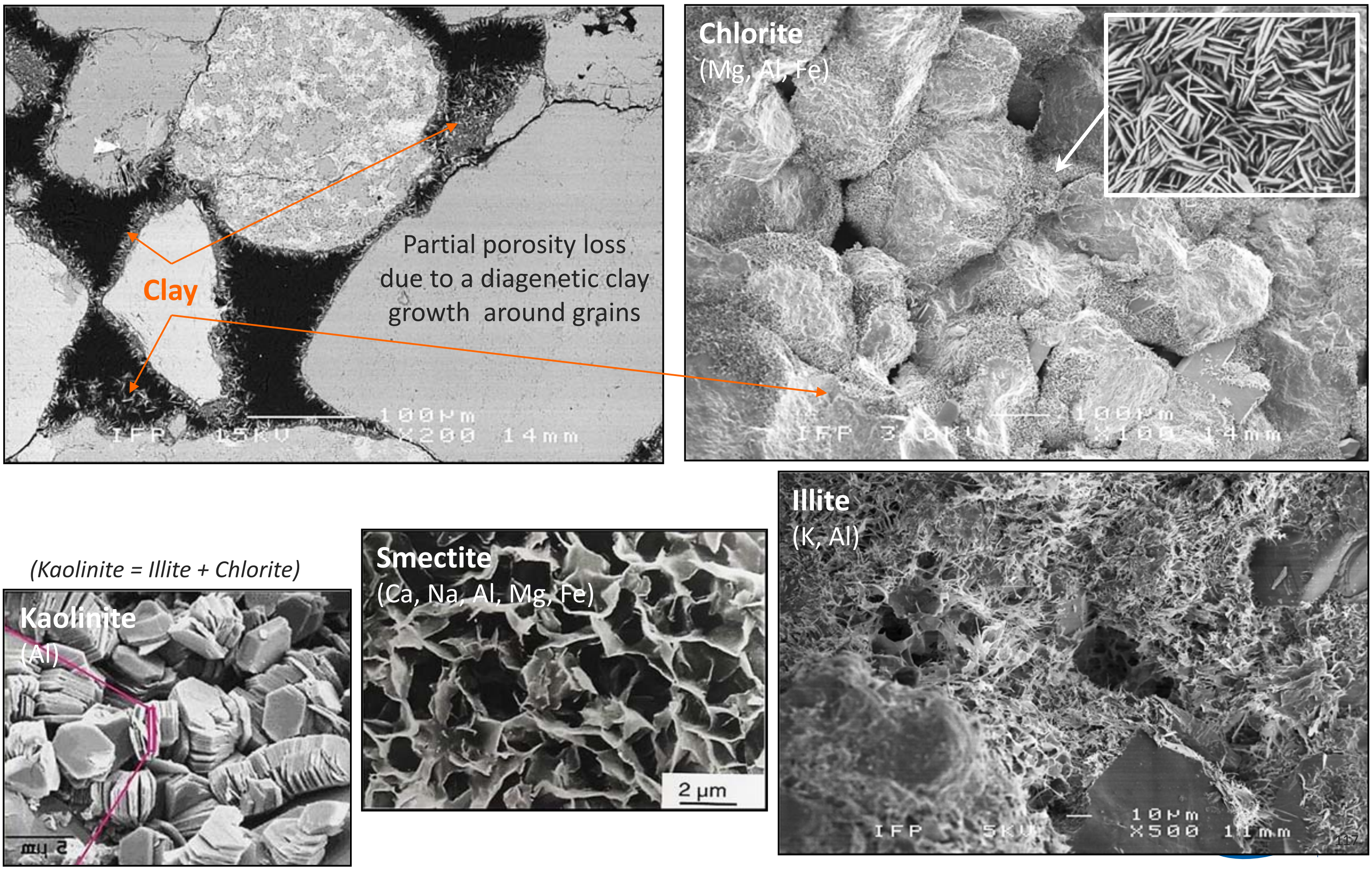
Shale
is a fissile, bedded sedimentary silicate rock with silt and clay-size particles

Claystone
is a non-bedded rock (generally diagenetical, formed *in situ*, within pores)

(*)
Carbonatic shale = Marl

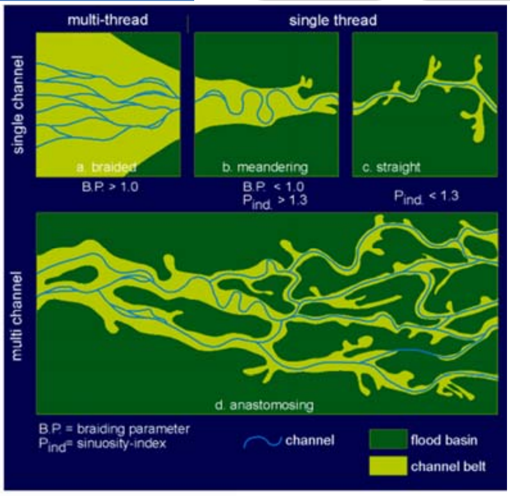
3D digital objects called vRocks are created for each SCAL sample and the connected pore volume (shown in blue in right hand image) is used to compute permeability using a Lattice Boltzmann method. Red is isolated porosity and green is organic material.

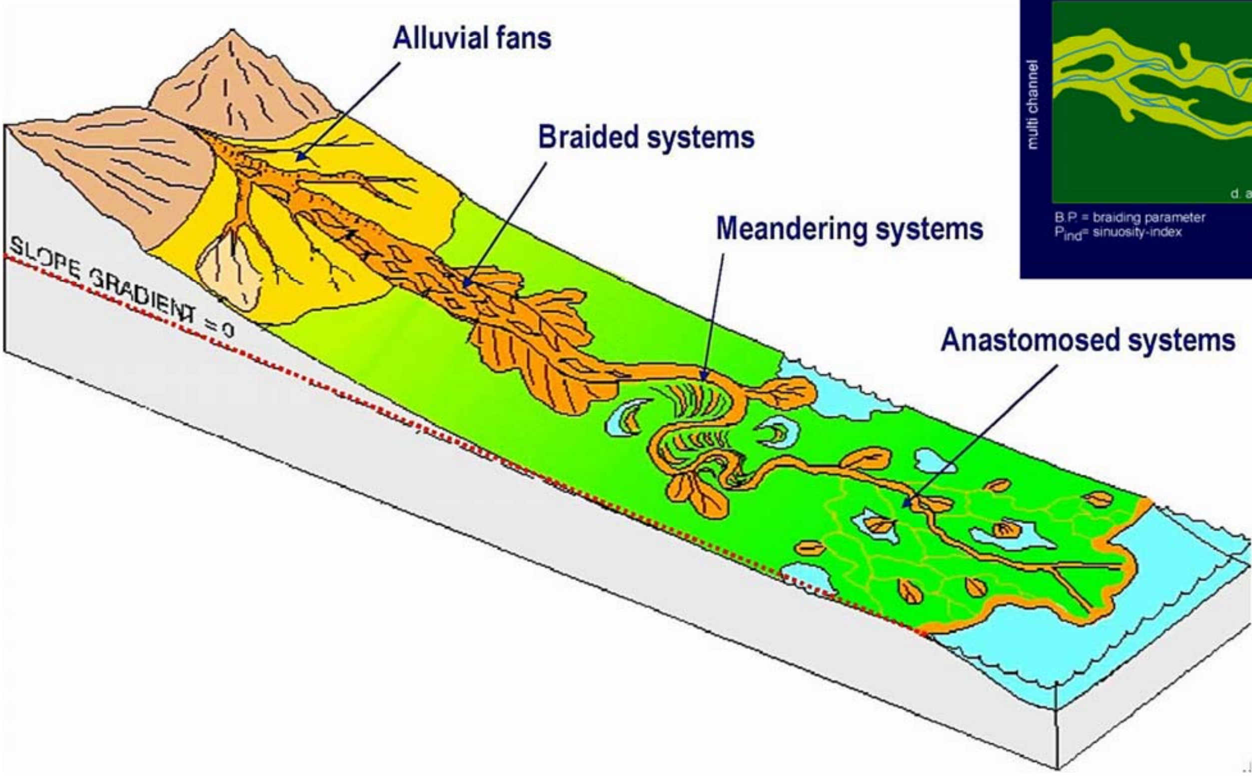
Porosity loss due to clay minerals (V_{clay})



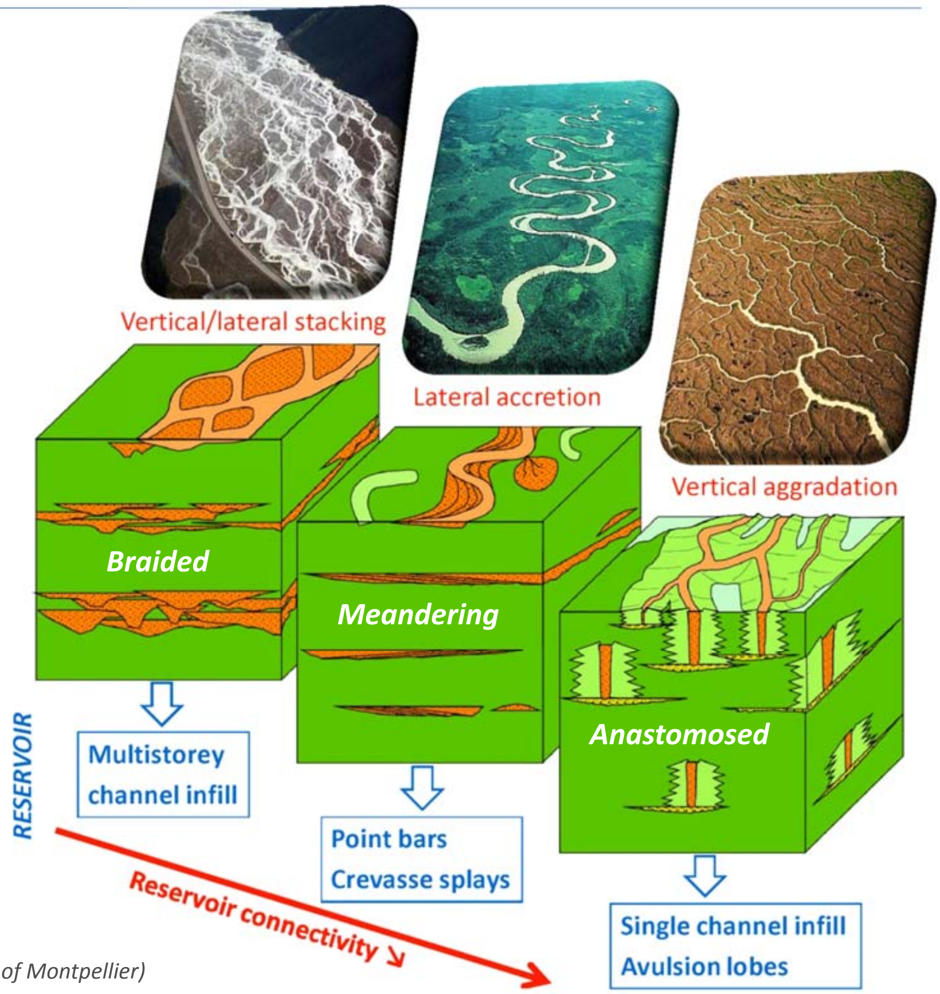
Siliciclastic continental depositional environments

Classification of fluvial styles
(Makaske, 1998)



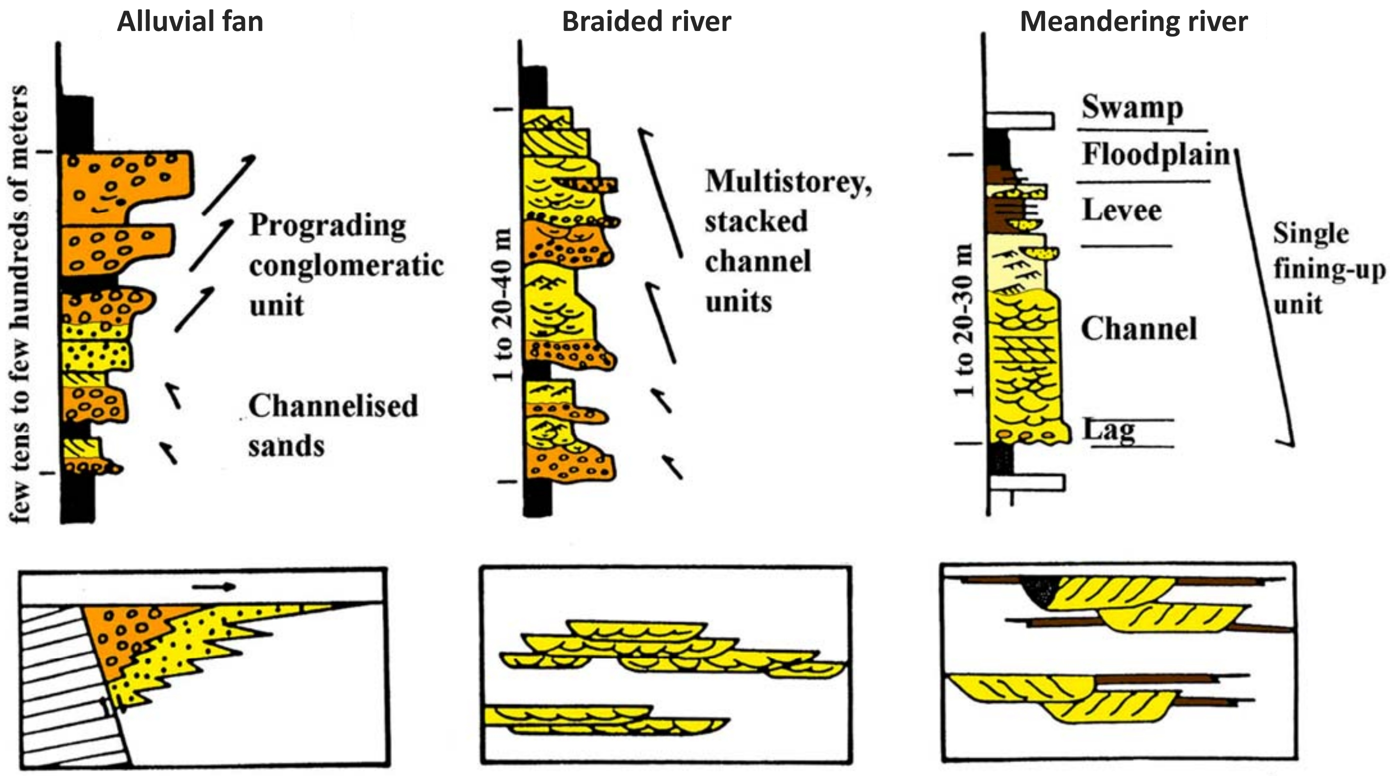


River facies vs Reservoir geometry



Courtesy: Pr. M. Lopez (U. of Montpellier)

Typical depositional sequences of fluvial sediments

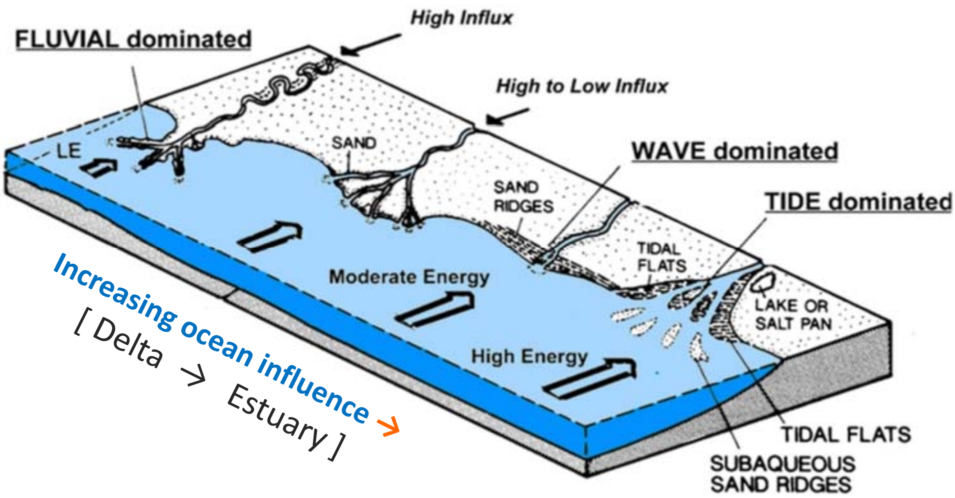


Tabular accumulations associated with active faults; thick deposits, but frequently low downdip extent

Widespread channelised sand sheets

Isolated point bar clusters

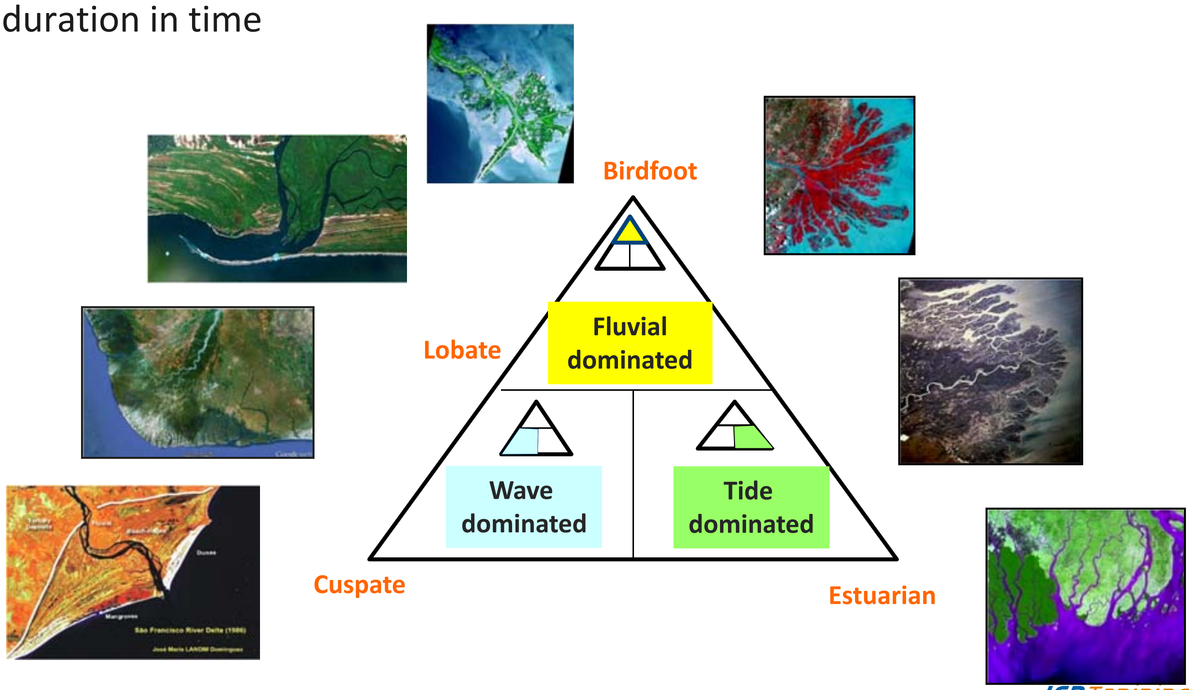
Delta shapes & energy



- **The delta morphology reflects the relative importance of fluvial, tidal, and wave processes, as well as sediment supply**
  - **River-dominated deltas** occur in microtidal settings with limited wave energy, where delta-lobe progradation is significant and redistribution of mouth bars is limited
  - **Wave-dominated deltas** are characterized by mouth bars reworked into shore-parallel sand bodies and beaches
  - **Tide-dominated deltas** exhibit tidal mudflats and mouth bars that are reworked into elongate sand bodies perpendicular to the shoreline

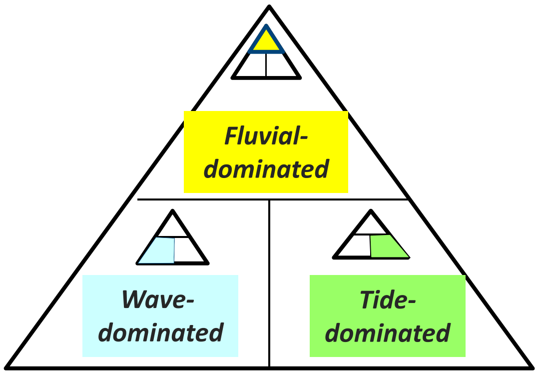
Delta shapes & energy

- **Morphological classification of deltas are based on delta front shape which reflects:**
  - The relation between the relative importance of rive, tide or wave processes
  - The sediment supply
  - The duration in time



Coastal systems and reservoir potentials

2. Reservoir bodies:
Mouth bar, and aggradational channels complexes located along the distributary:
Limited lateral extension



1. Reservoir bodies:
Beach barrier island, very good lateral continuity, well sorted sandbodies and clay-free:
Best reservoir

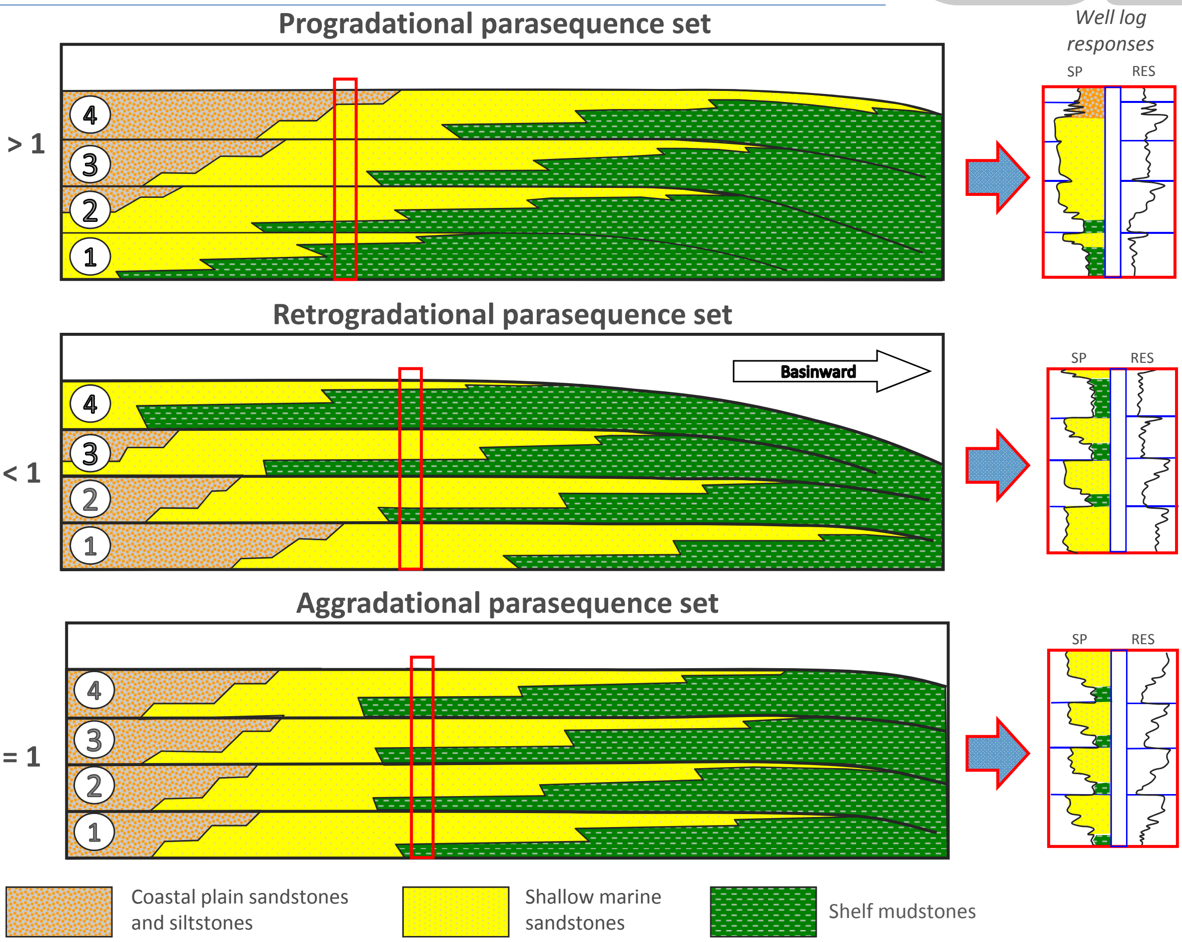
3. Reservoir bodies:
Isolated tidal bar, poor continuity and extension. Well sorted sandstone, but lot of clay drapes due to intertidal processes: **Discontinuous reservoir**

Parasequences

Sedimentation rate / Accommodation rate > 1

Sedimentation rate / Accommodation rate < 1

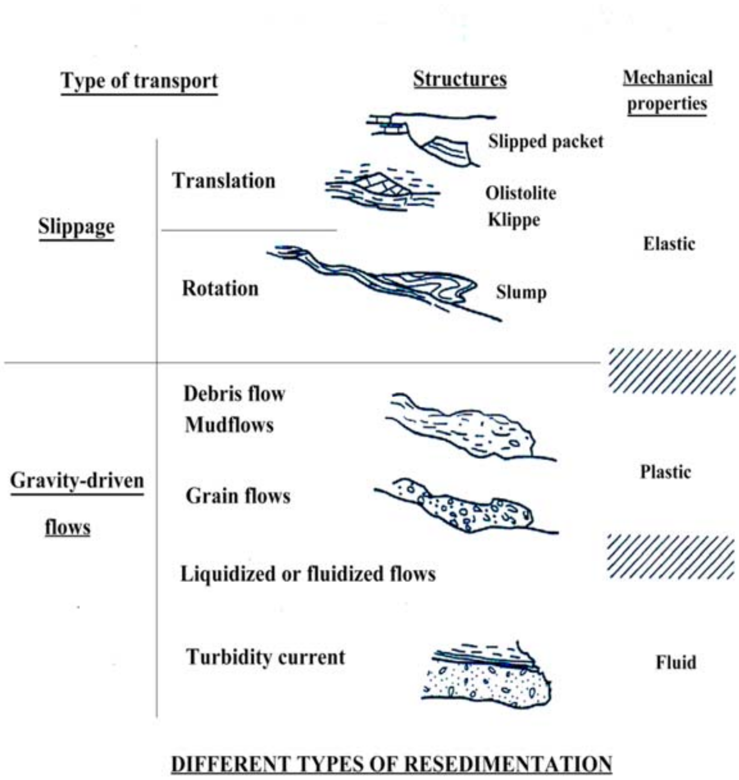
Sedimentation rate / Accommodation rate = 1

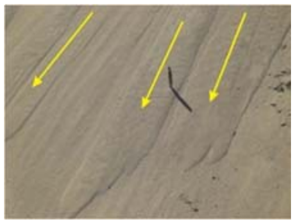


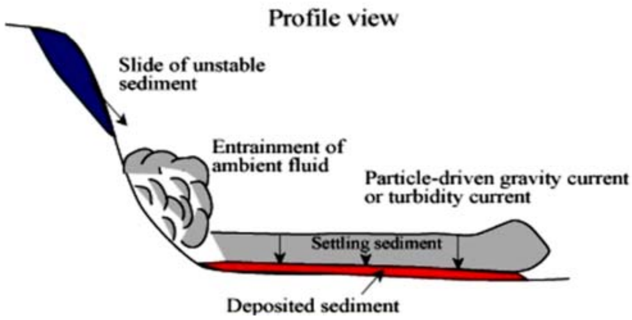
1 *Individual parasequences*

MITCHUM and VAN WAGONER 1991

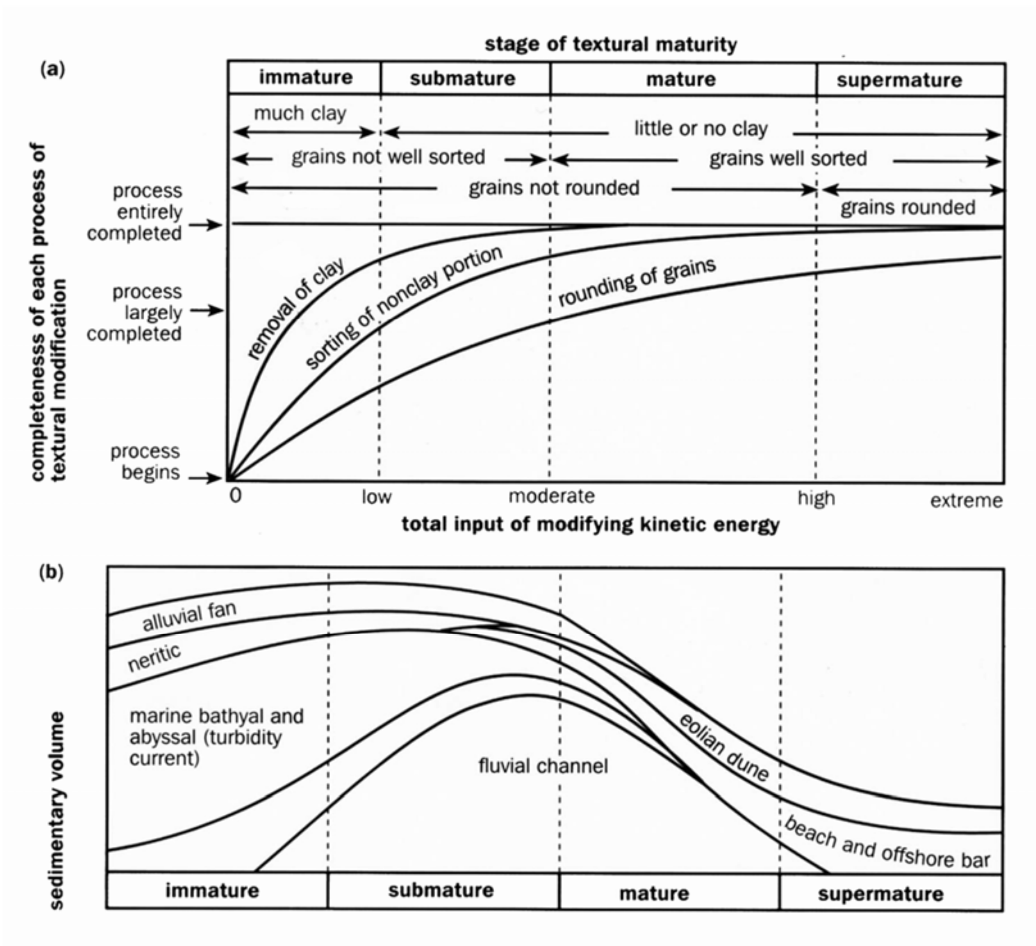
Gravity flows







Sediment maturity for reservoir generation



Vertical proportion curves (VPC)

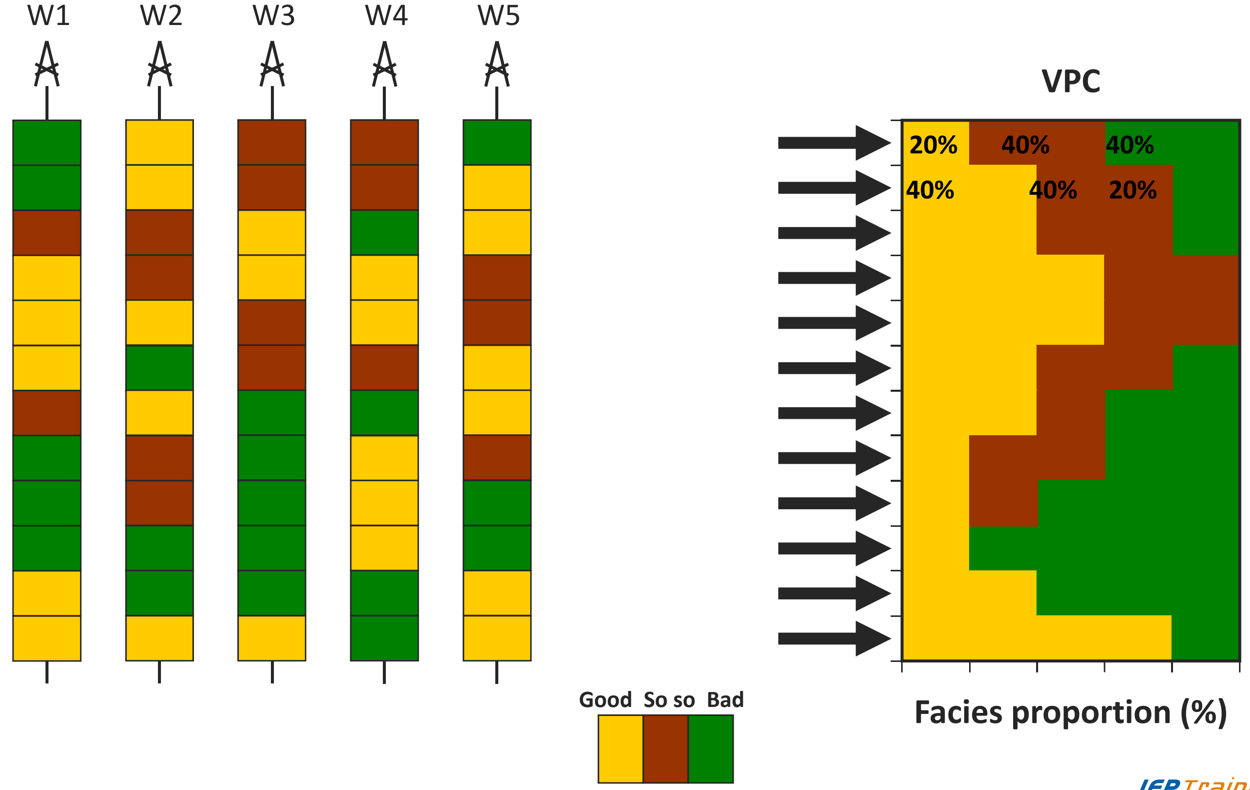
Vertical Proportion Curve (VPC)

- **VPC**
  - A key **statistical tool** for facies characterization
  - The **bridge** (“hinge”) between **observation** (description) and **quantification** (digitizing)

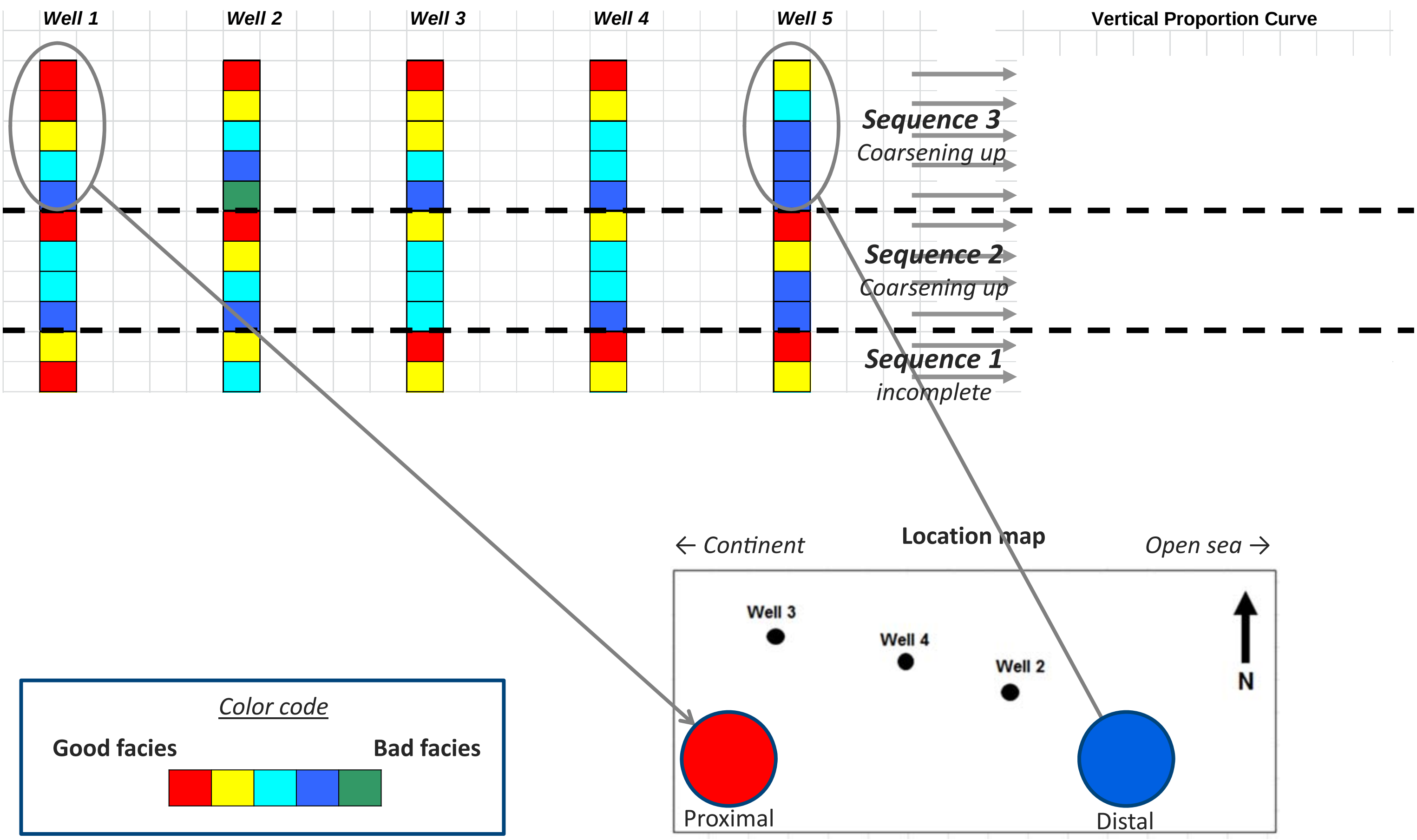
  → **An indispensable step/tool prior to numerical modeling**

Vertical Proportion Curve (VPC) Principle

Definition



Vertical Proportion Curve



9. Rock typing

Slides extracted from Dr. ***Frédérique Fournier****'s presentation*

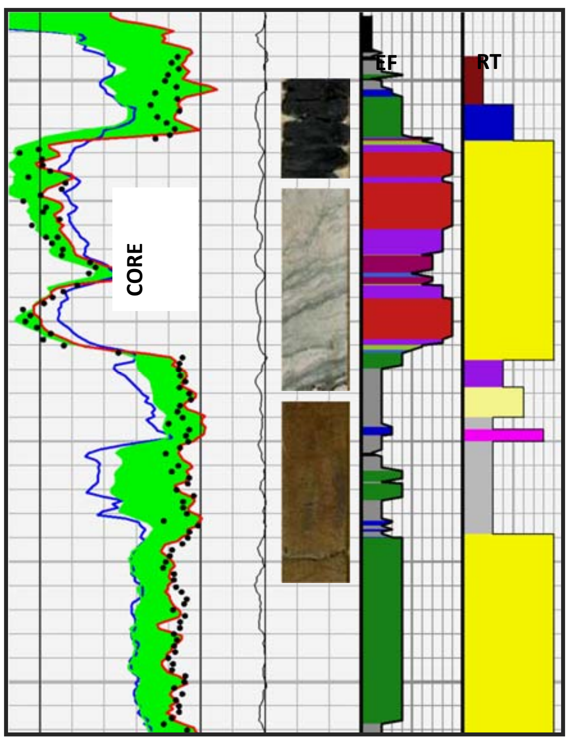
- **Reference publications from:**
  - The French Petroleum Institute (IFPen)
  - Beicip-Franlab (IFP Group)

Course objectives

- **To understand what electro-facies and rock types are:**
  - correlate, combine and integrate consistent information from logs, core description and petrophysics
  - basics of electrofacies identification principles

- **To identify the connection** with both **geological** and **reservoir models** building processes

- To be aware of **main pitfalls** when defining rock types

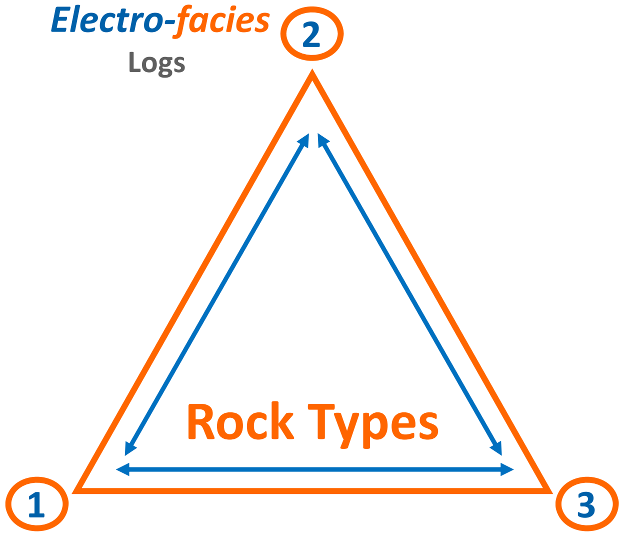


Rock Type definition

Rock typing = Facies integration

Objective: to define rock types in all wells

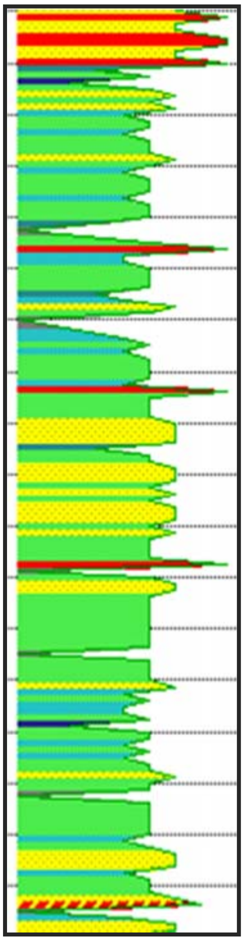
Electro-facies
Logs



Litho-facies
Stratigraphic framework and core/thin section description

Petro-facies
Routine core measurements (CCAL & SCAL)

Rock Typing: integration of all facies

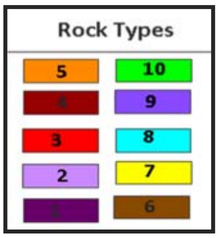


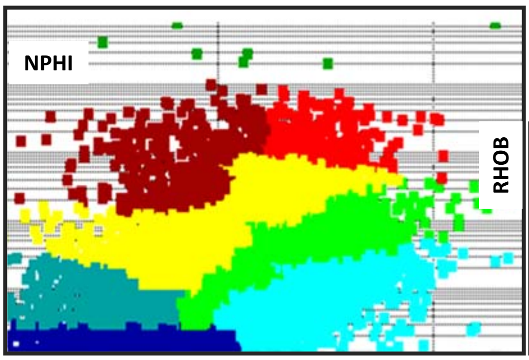
- **Litho-facies: sedimentological facies and petrology**
- **Electro-facies: well log analysis**
- **Petro-facies: core analysis and petrophysical measurements**

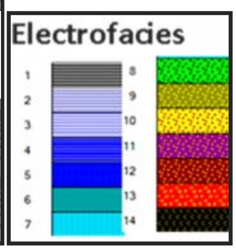
→ **Rock Types are determined:**

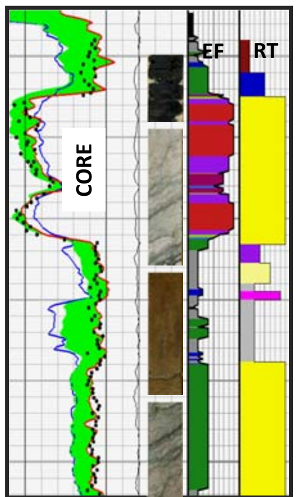
- in a specific geological context
- with a specific log suite
- for both cored and non-cored intervals

RT should integrate **capillary pressure** data





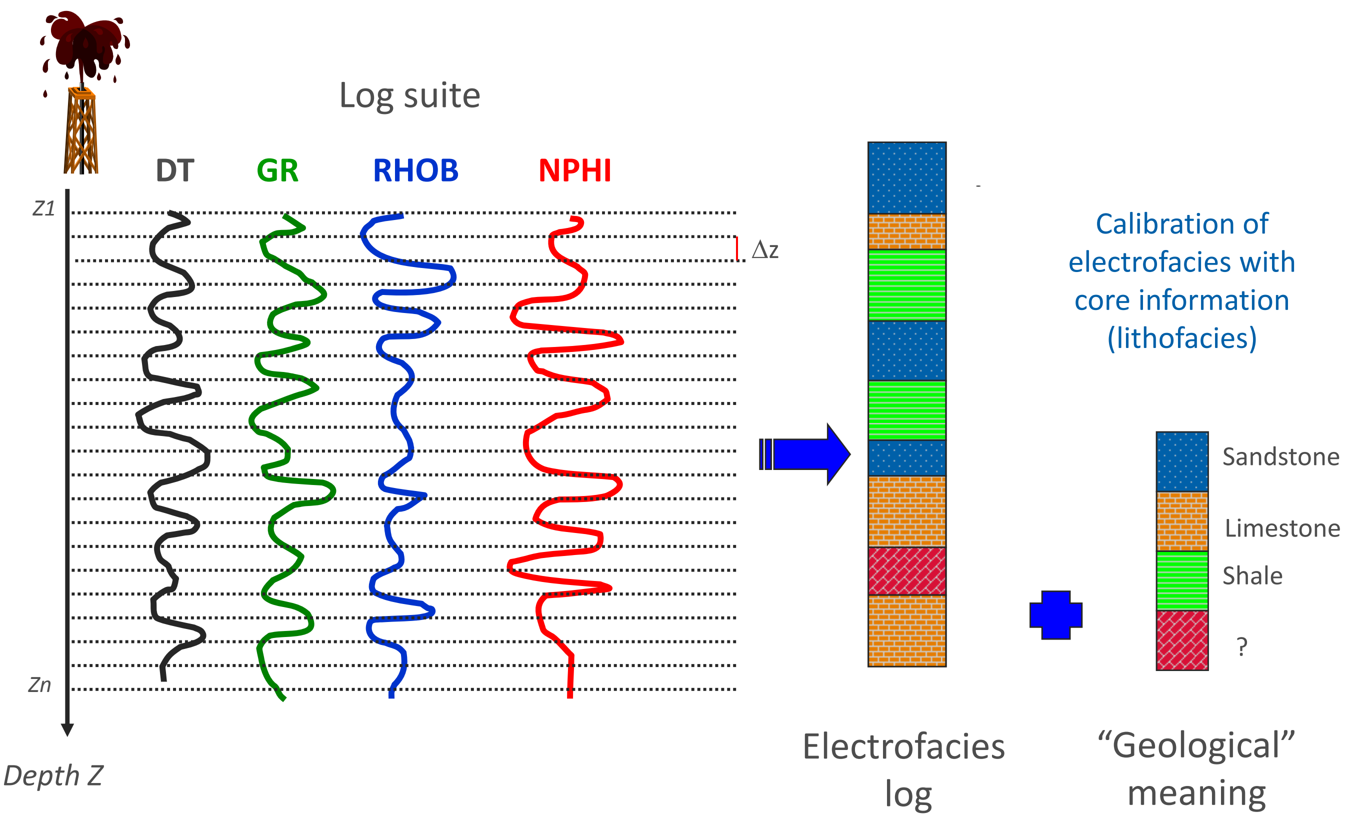




Rock typing workflow

- **Select "Reference" wells with:**
  - Core descriptions
  - Reliable and complete log suites (curve combinations)
  - Corresponding petrophysical measurements (core lab)
  - → The "master" well needs to be representative of main geological variations within studied field
- **Integrate logs and core** description through electrofacies analysis
- **Convert electrofacies into rock types** via integration and calibration **of petrophysical data (CCAL or SCAL) – i.e. petrofacies**
- **Propagate** rock types (or electrofacies only, if no core) to the other wells of the field
  - Gaps may show up…
  - Seismofacies can also be used for propagation (3D seismic scale is closer to dynamic model scale)

Automated log data analysis

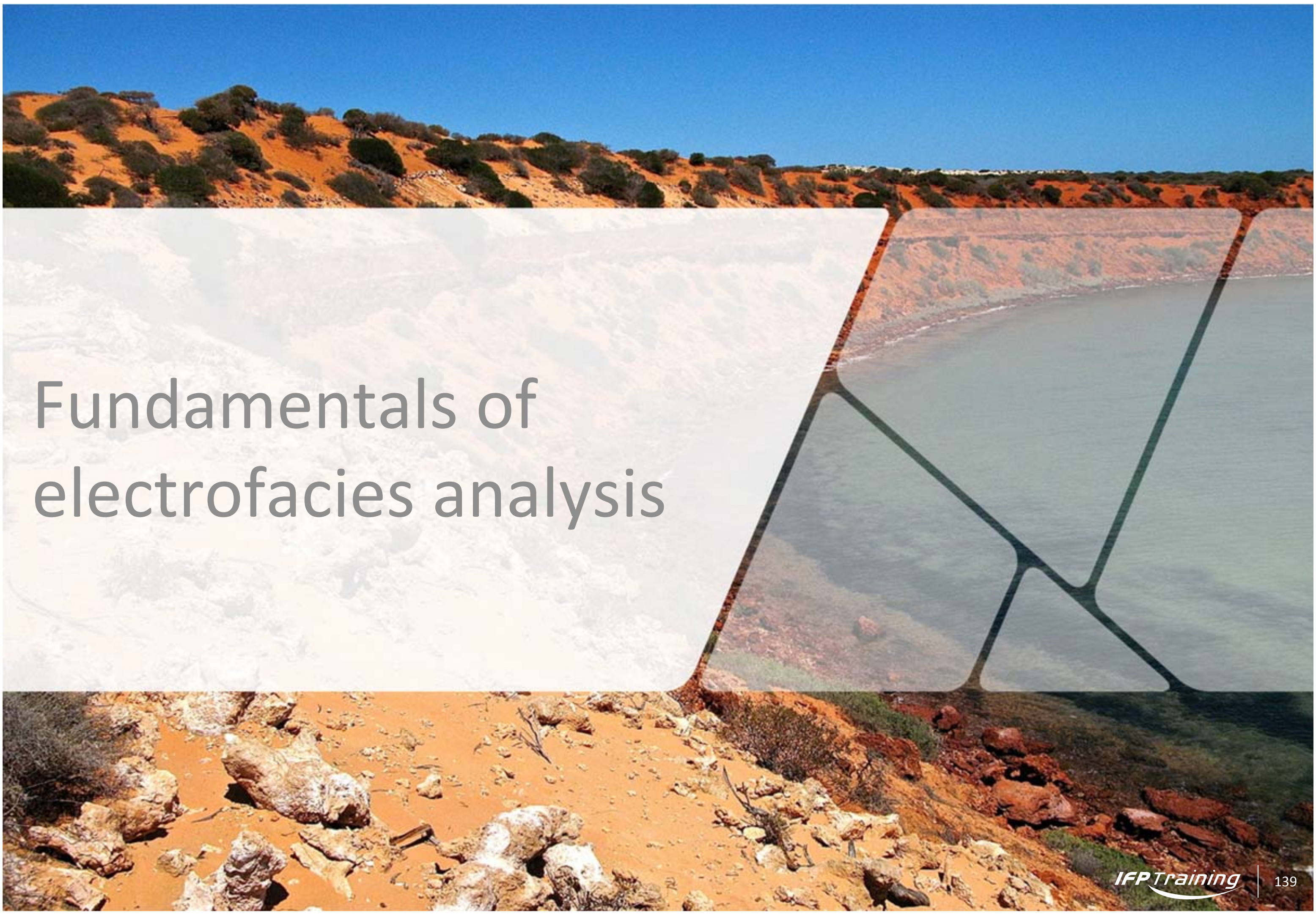


Rock type definition

- **Rock type = homogeneous response in terms of Phi/K**
  - → **Preliminary flow unit determination** (preparing dynamic model)
- **Homogeneous fluid flow properties**
  - Capillary pressure curves
  - Relative permeabilities
  - Introduced in reservoir simulation model
- **Electrofacies interpretation** with **PHI/K** plots (core data), **electrofacies** gathering and connection **with capillary pressure (Pc) curves**
- **Electrofacies analysis** using **[Phi/K]-related logs** (or interpreted logs)

Presentation summary

- **Fundamentals of electrofacies analysis**
  - Bases of electro-facies analysis
  - Electro-facies identification techniques
    - Non-supervised approach
    - Supervised approach
    - Example from a real case
- **Petrofacies determination**



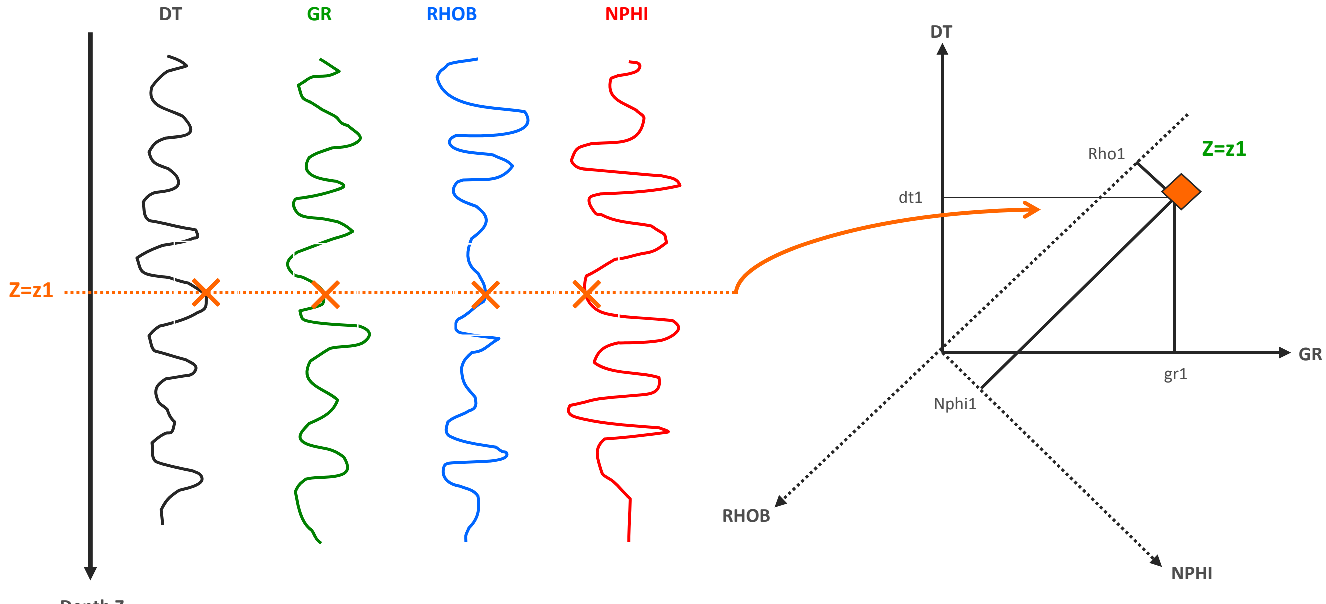
Fundamentals of electrofacies analysis

Base of electrofacies analysis

- **Two steps:**
  - Step 1 : Representation of **log** data:
    - **Select** appropriate **log curves**
    - Tie back to **core** descriptions
  - Step 2 : Segmentation of data:
    - **Identify clusters** in the representation space to identify electrofacies
    - → each cluster will correspond to a specific electrofacies

Data representation

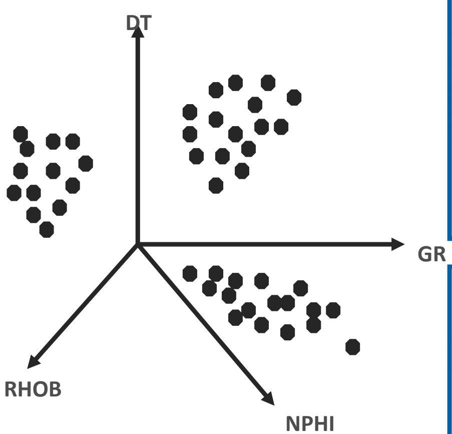
- The **representation space** is defined by a specific combination of analyzed logs ("extended" cross-plot)

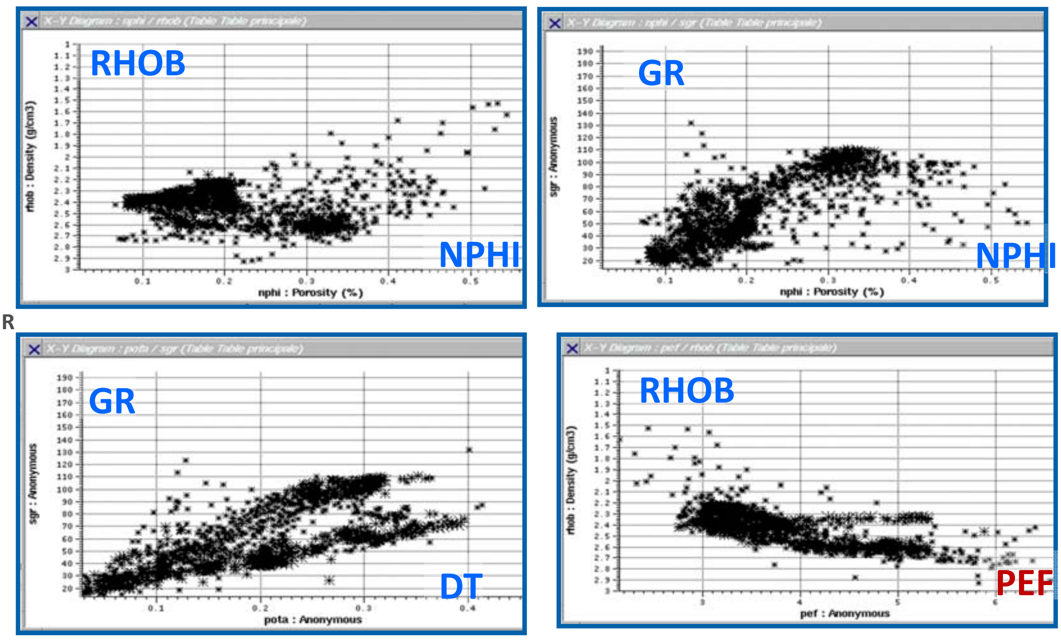


Multivariate cluster of points

Representation of log data (space)

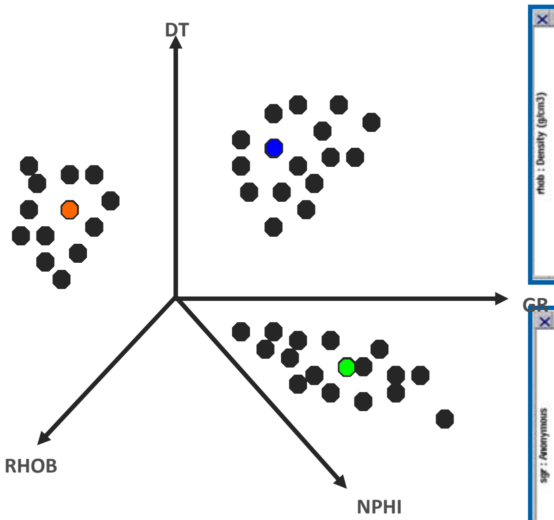
- **Step 1**: representation of information contained in the data points (several depth intervals/several wells)

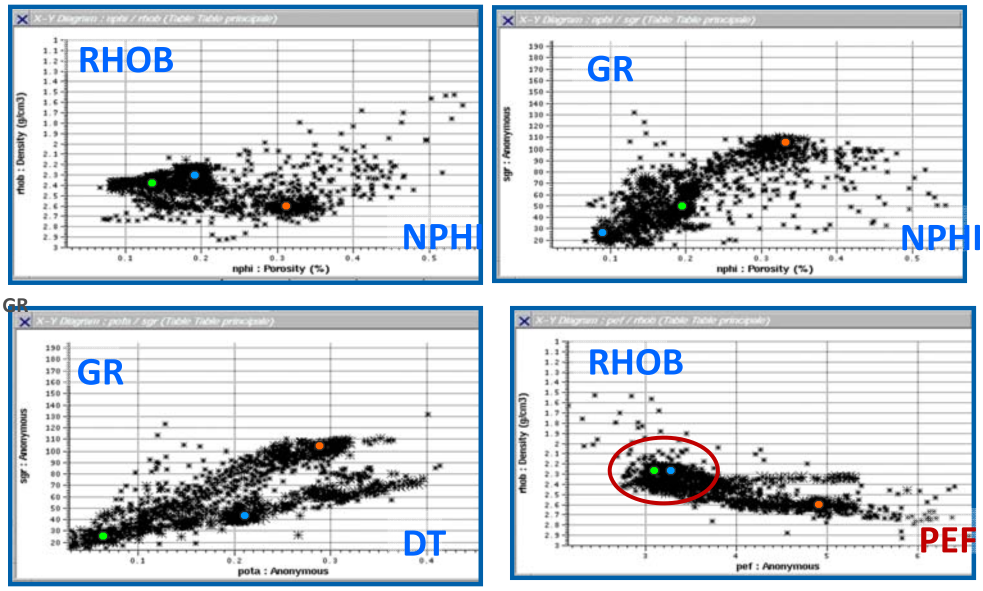




Segmentation of data: cluster detection

- **Step 2**: aggregation of points that are close in the representation space to form distinct clusters

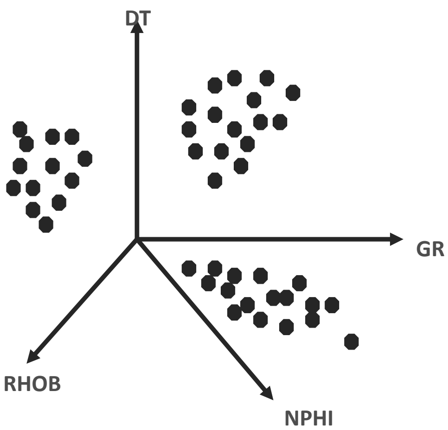


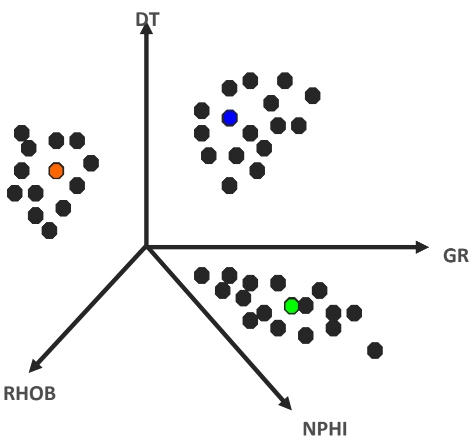


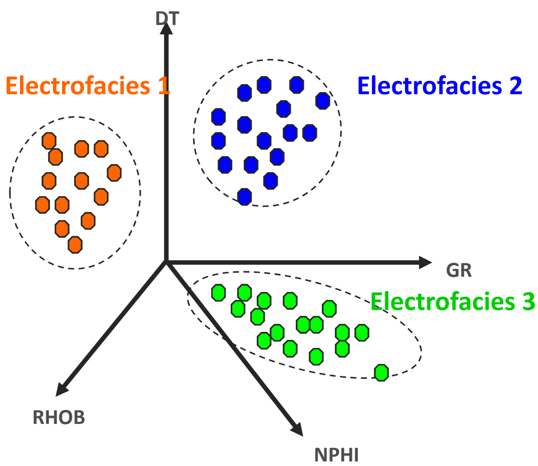
Cluster identification/definition

Segmentation: cluster definition

- **Step 2bis**: define each cluster with a probabilistic frame as an “electrofacies”







Cluster definition/Electrofacies identification

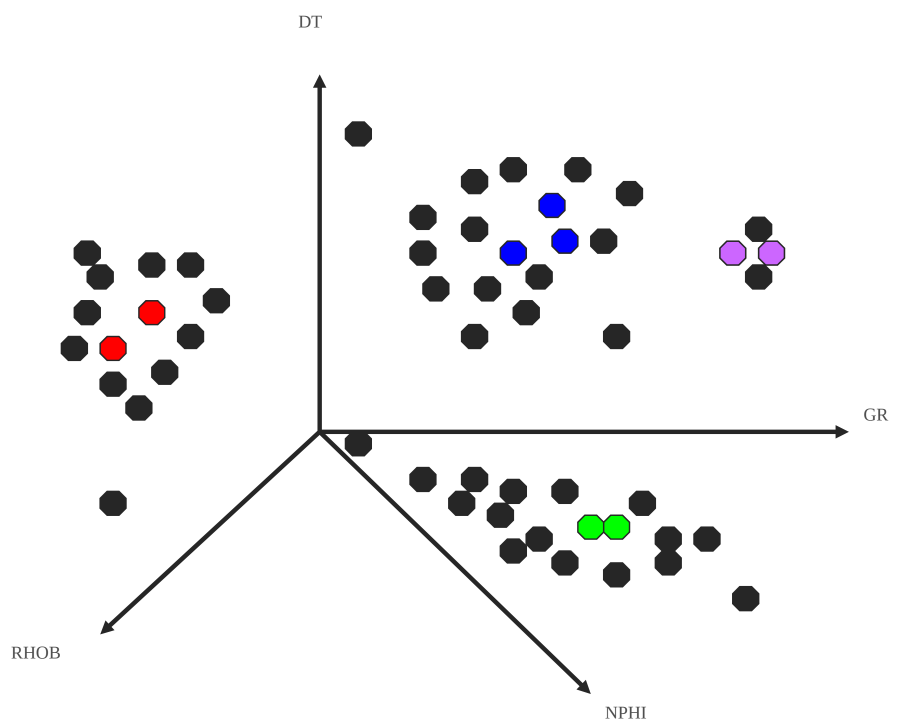
- **Based on optimization procedures and cluster separation with quality criteria**

- **Cluster definition carried out in a probabilistic frame**
  - statistical pattern recognition that provides uncertainty characterization

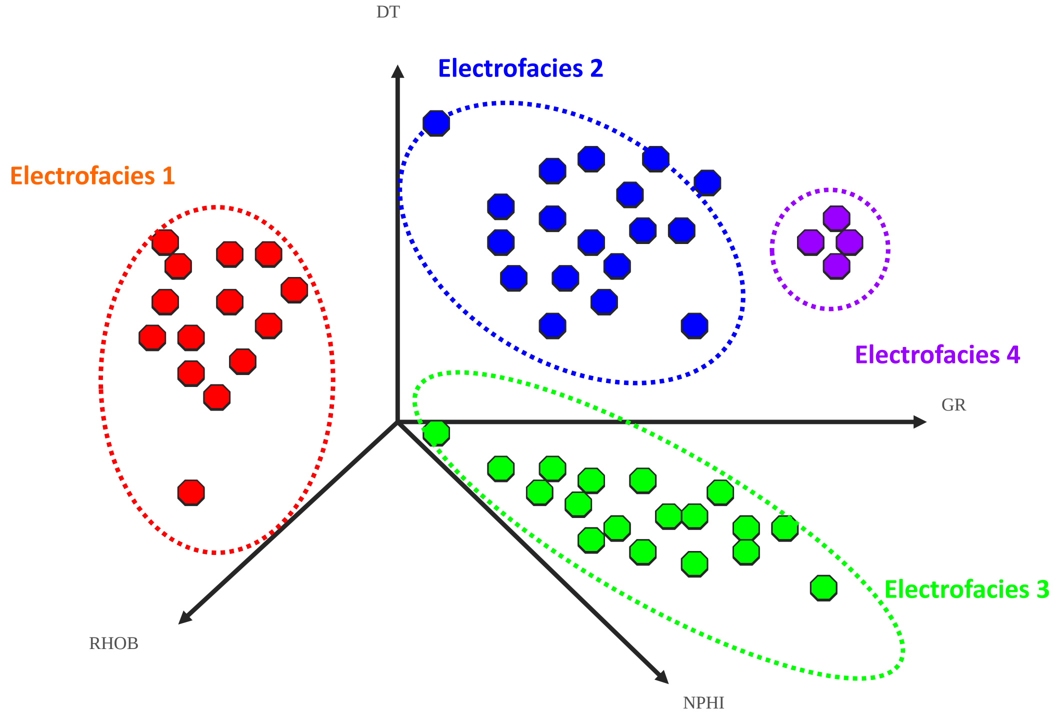
- **Key steps in process in segmentation process**
  - Select logs (QCed and normalized)
  - Determine the number of clusters (electrofacies) present in the data (***step1***)
  - Assign each depth point from a specific well a cluster (classification) (***step2***)
  - Evaluate the uncertainty associated with classification

- **Electrofacies analysis techniques : two approaches**
  - **Non-supervised** method
  - **Supervised** method

Non-supervised electrofacies analysis (step 1)



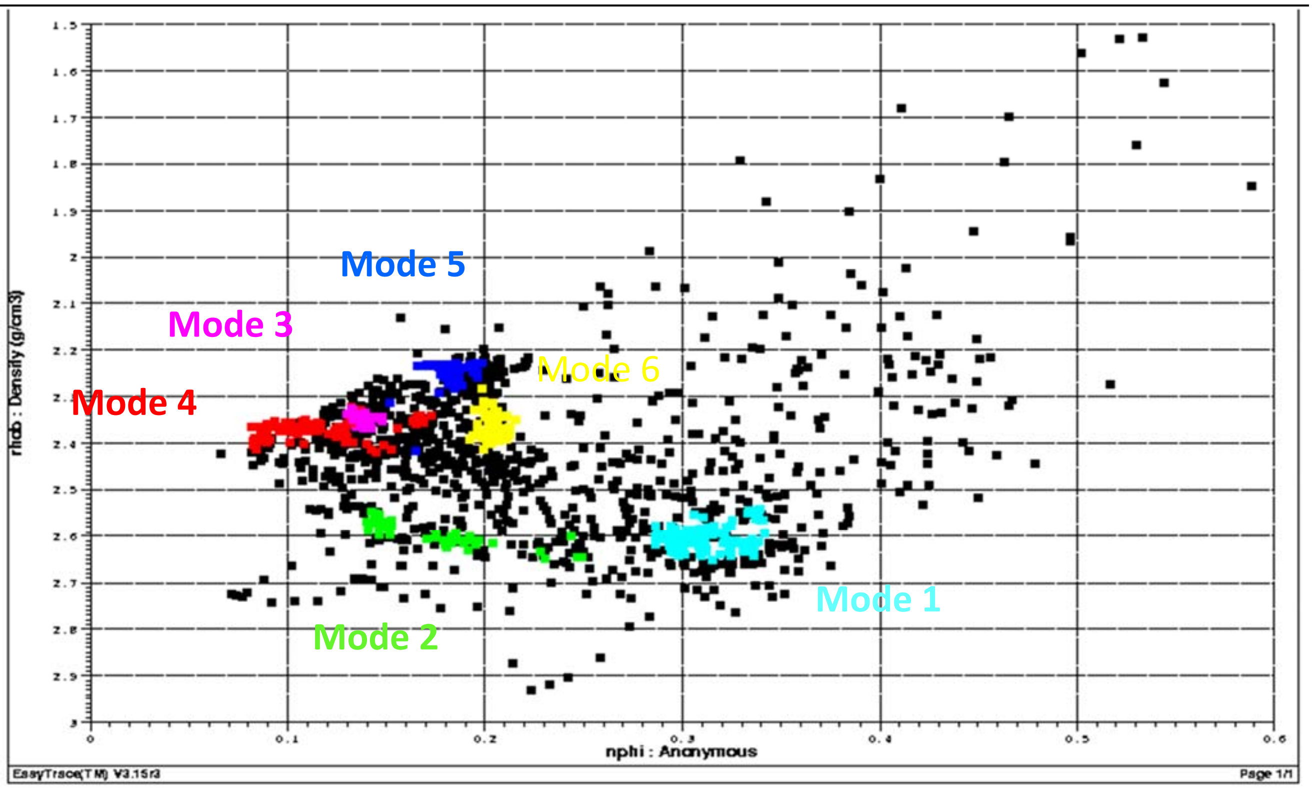
Non-supervised electrofacies analysis (step 2)



How to determine the appropriate number of clusters ?

Non-supervised electrofacies analysis

step:1

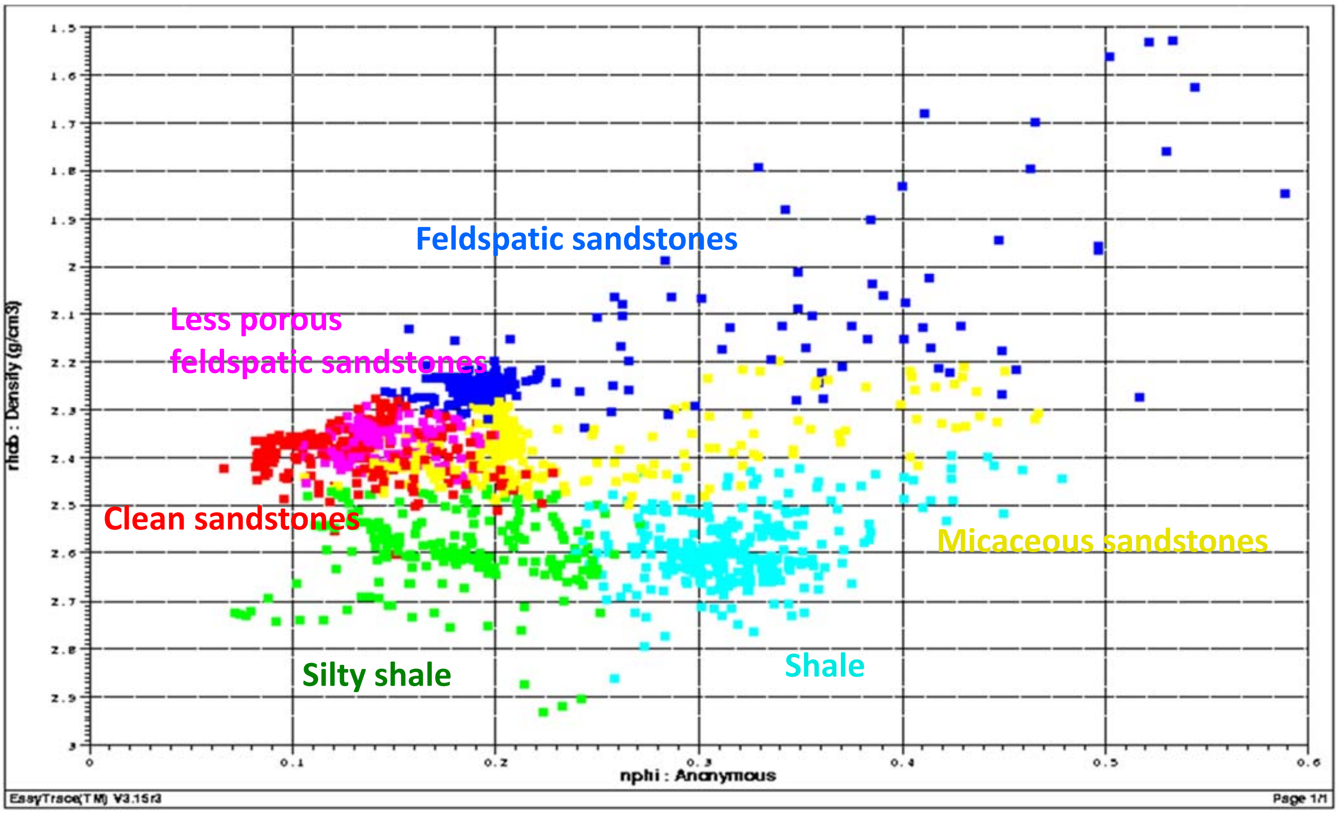


Neutron/Density cross-plot

Non-supervised electrofacies analysis

step 2

NPHI/RHOB

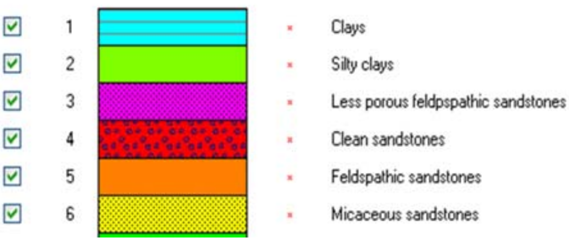


Limited discrimination between red, pink and yellow modes on NPHI/RHOB plot

Non-supervised electrofacies analysis

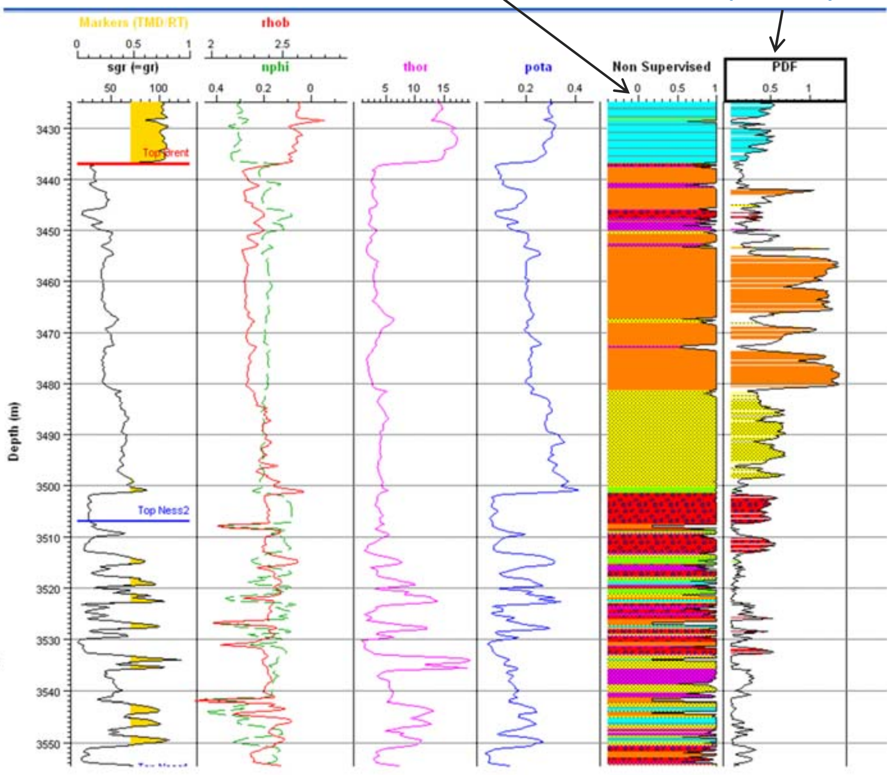
Final results

- **Results:**
  - **A column of electrofacies interpreted *a posteriori*** with core description or lab measurement
  - **An evaluation of uncertainty** (probability of good classification)



Complete assignment

Good assignment probability



(within Probability outline)

Points from modes

Non-supervised analysis – Key points

- **Provides an automatic determination of geologically-significant electrofacies, calibrated with core/cutting information or quick-look interpretation - but that could also be related to anomalous data…**

- **Method based on density function analysis: a precise approach that provides probabilities of good assignment to different classes, but requires heavy computing time.**
  - The classes that are found are related to dense areas in the cloud of points (involved distance is density-based)
  - Thorough log QC and normalization are mandatory to get reliable results

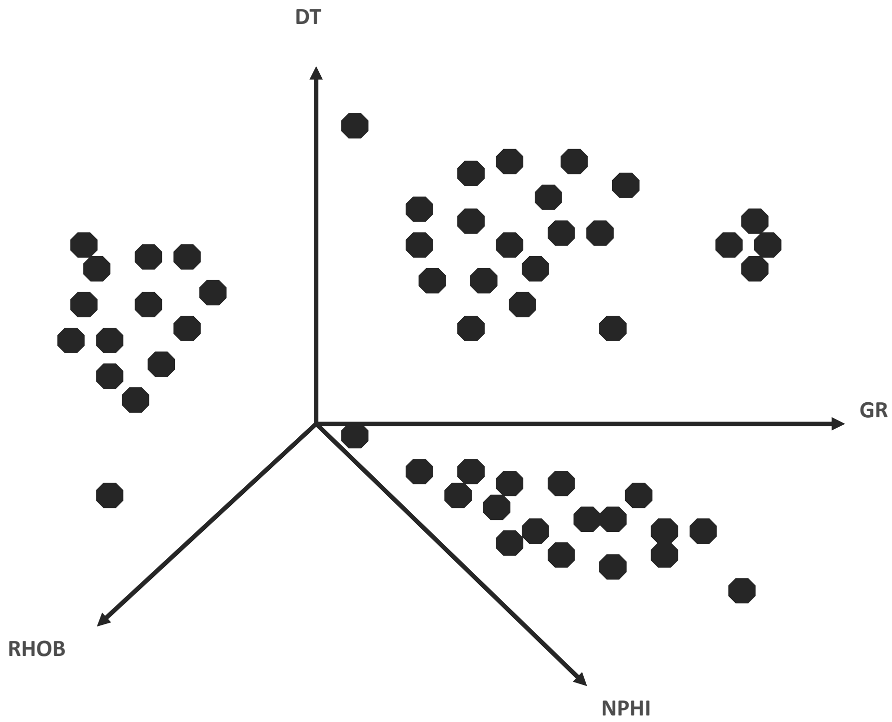
Supervised electrofacies analysis

Principle

- **Based on the statistical technique of Discriminating Analysis (DA)**
- **A training sample (TS) is defined with depth points for which the a-priori target information is available: electrofacies, lithofacies or rock types are known at these depths:**
  - Characteristic values in quick look analysis
  - Cored information
  - Lab measurements
- **Check that a-priori electrofacies classes have typical log responses (descriptive step)**
  - TS should form distinct clusters in the log representation space
- **Build a classification rule (predictive step)**
  - Assign each depth point an electrofacies
  - Estimate related uncertainty
- **The classification rule is defined from TS statistical characteristics**

Supervised electrofacies analysis

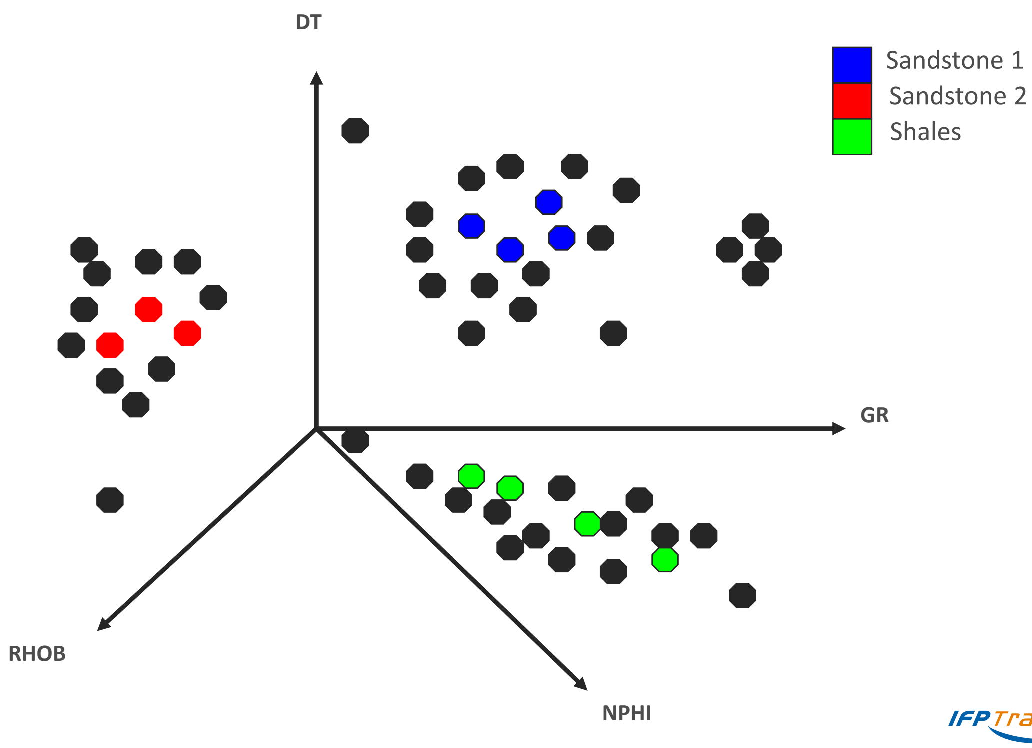
Method - 1/4



Supervised electrofacies analysis

Method - 2/4

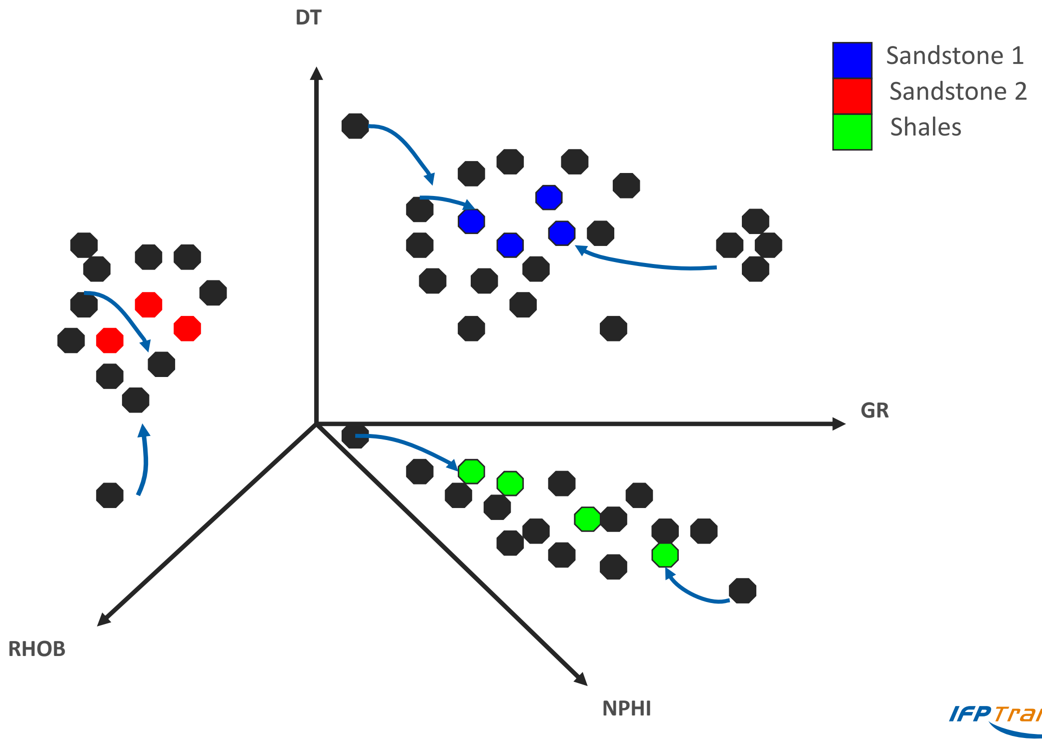
- In color, depth points included in the training sample
- In black: other “anonymous” depth points



Supervised electrofacies analysis

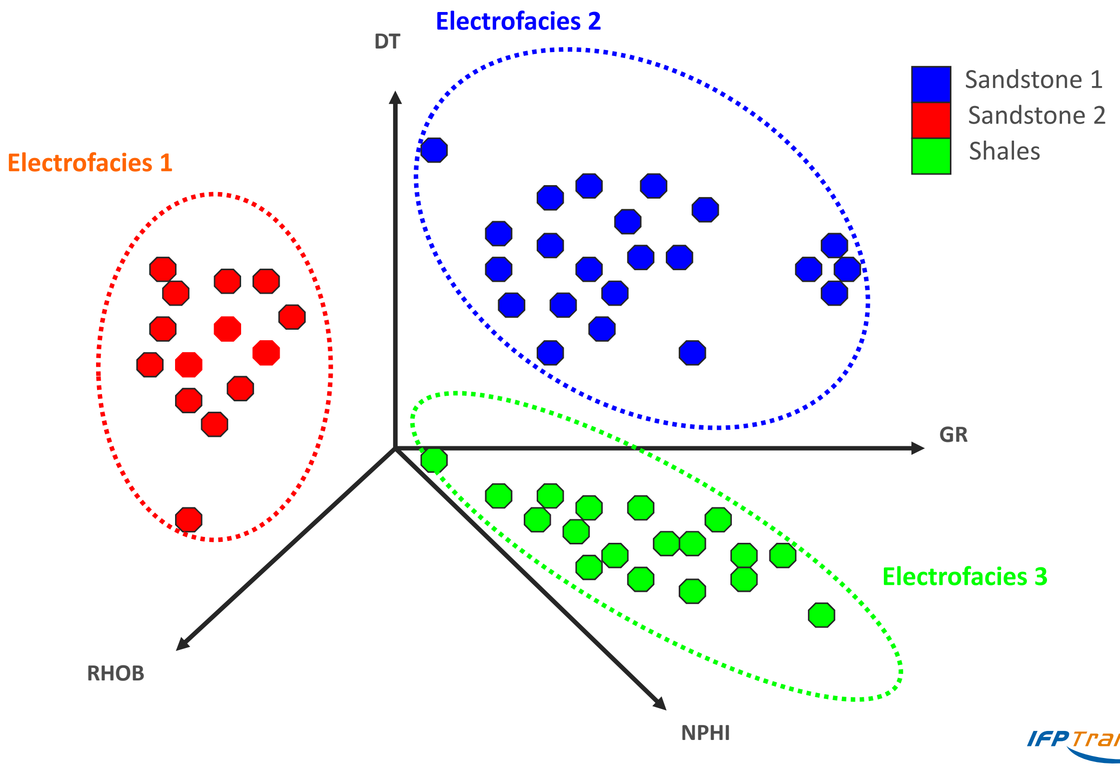
Method - 3/4

- In color, depth points included in the training sample
- In black: other “anonymous” depth points



Supervised electrofacies analysis

Method - 4/4

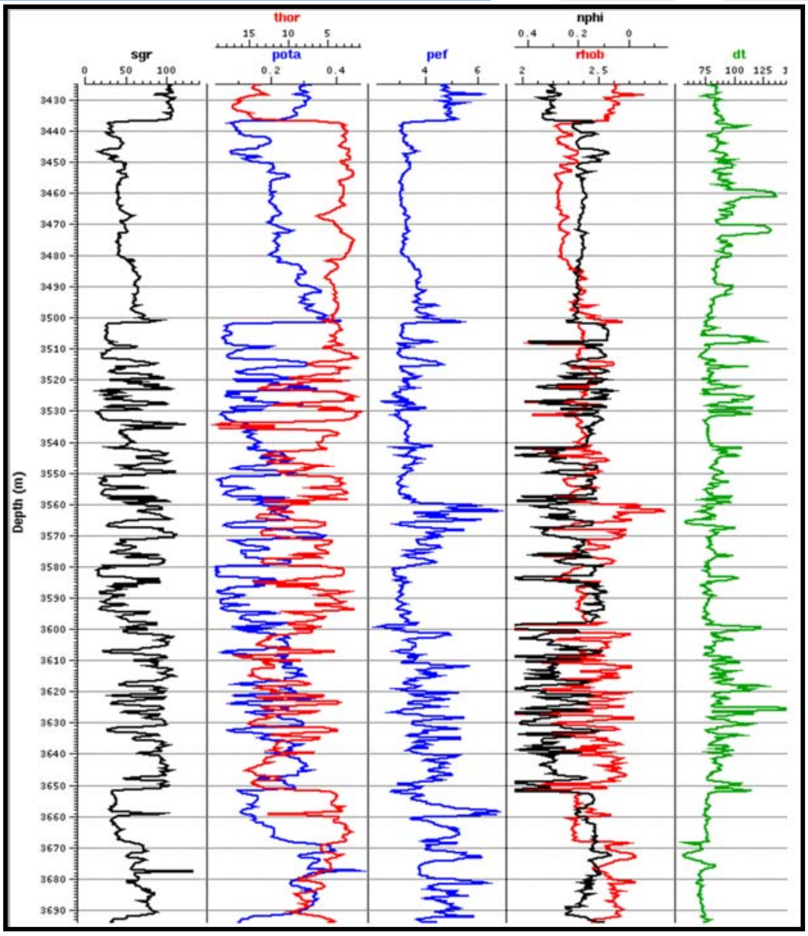


Supervised electrofacies analysis

Example from a real case (cont'd)

- **Available information set:**
  - Reservoir in fluvial-deltaic environment (Brent)
  - Suite of 7 logs
    - SGR, POTA, THOR, RHOB, NPHI, DT and PEF

- **Data for supervision:**
  - Core descriptions
  - Petrophysical data
    - Phi-K plug measurements



Supervised electrofacies analysis

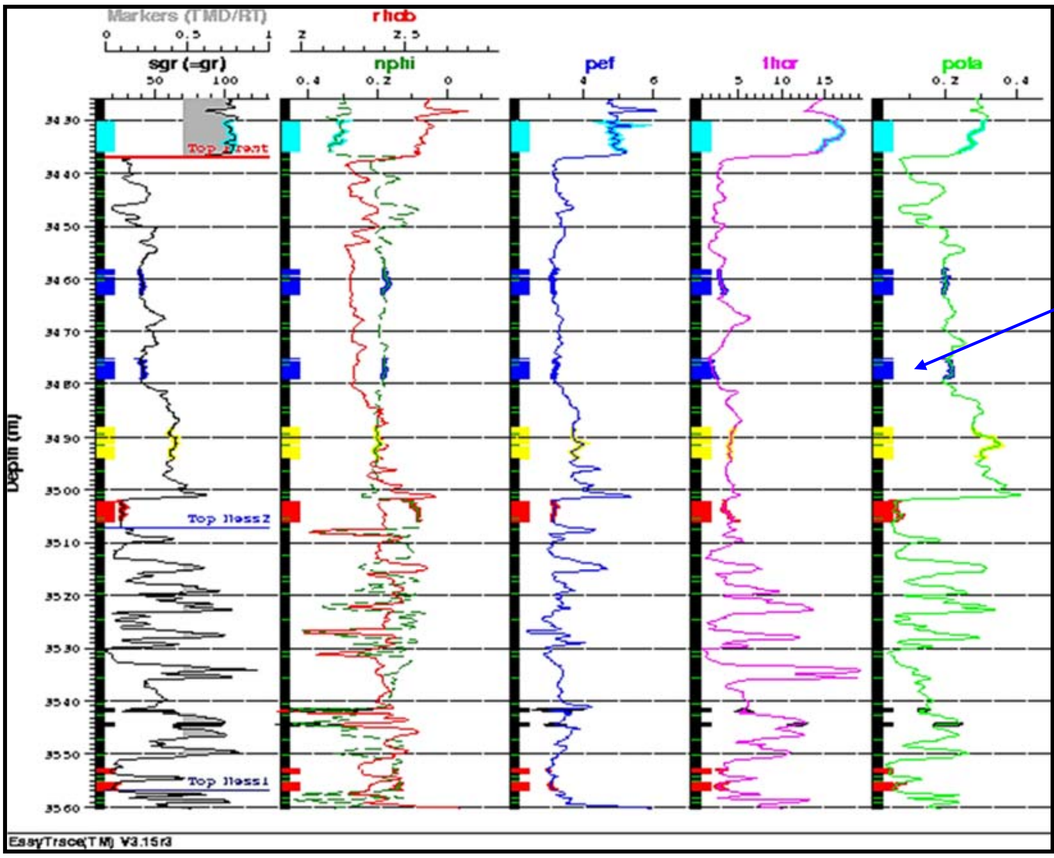
Training sample definition

- **A set of 3 logs is selected**
  - NPHI, RHOB, SGR (present in all wells)
- **6 training classes are defined (from quick-look analysis and core description)**
  - Class 1: clean sandstone (**red**, on cross-plots)
  - Class 2: feldspatic (radioactive) sandstone (**dark blue**)
  - Class 3: micaceous sandstone (**yellow**)
  - Class 4: silt (**green**)
  - Class 5: shale (**light blue**)
  - Class 6: coal (**black**)

→ **Association of observed lithofacies with measured electrofacies (i.e. electrofacies calibration)**

Supervised electrofacies analysis

Selection of training samples

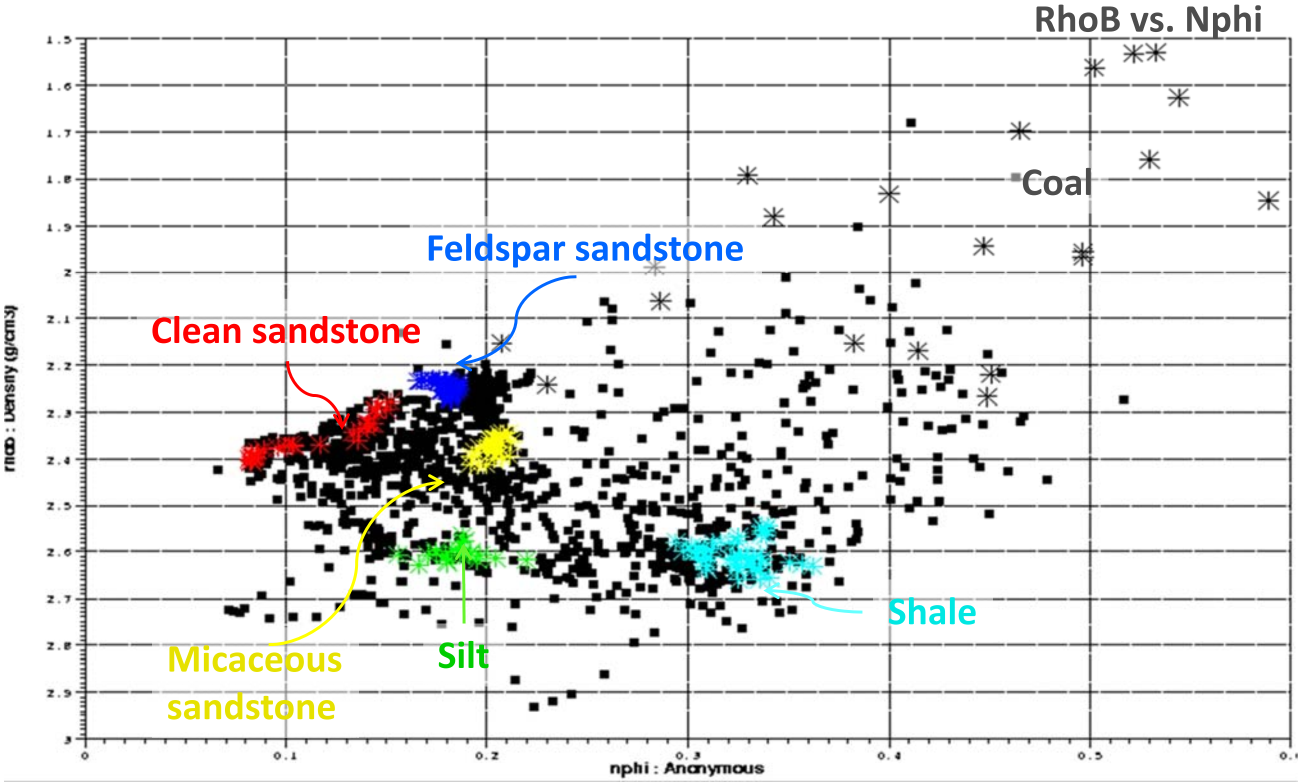


Highlighted depths were selected as training samples

[✱ points on Xplots]

Supervised electrofacies analysis

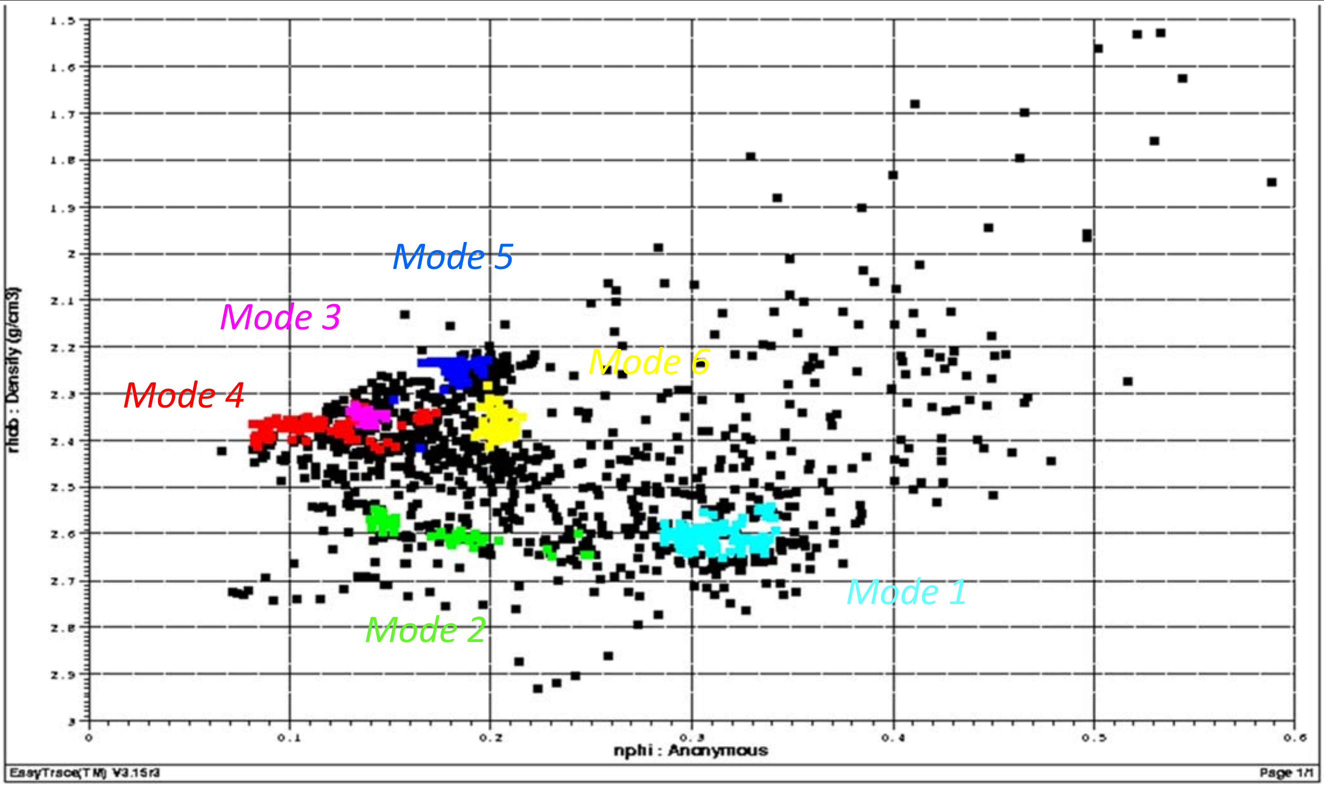
Supervised clustering: training samples on cross-plot



✱✱✱✱✱✱ Training samples

Supervised electrofacies analysis

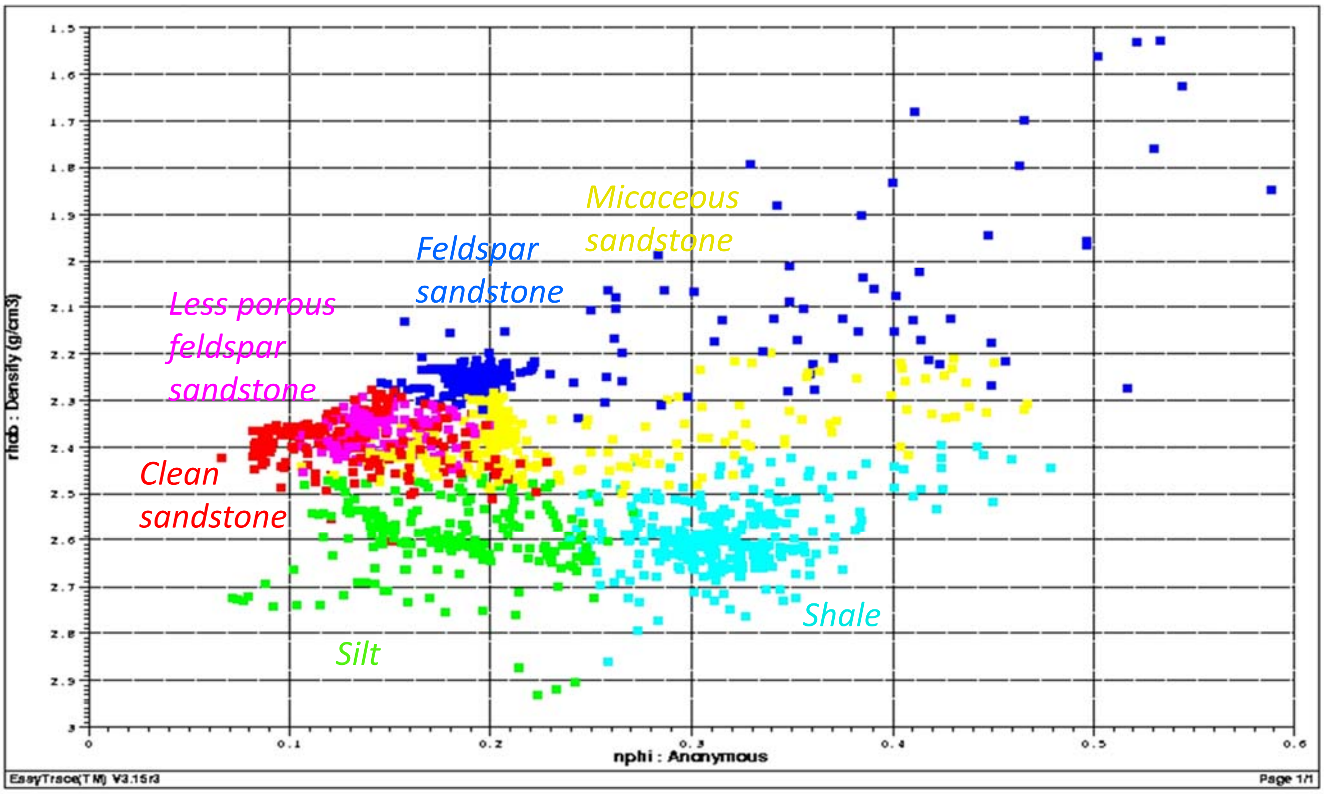
Non-supervised clustering



Neutron/Density cross-plot

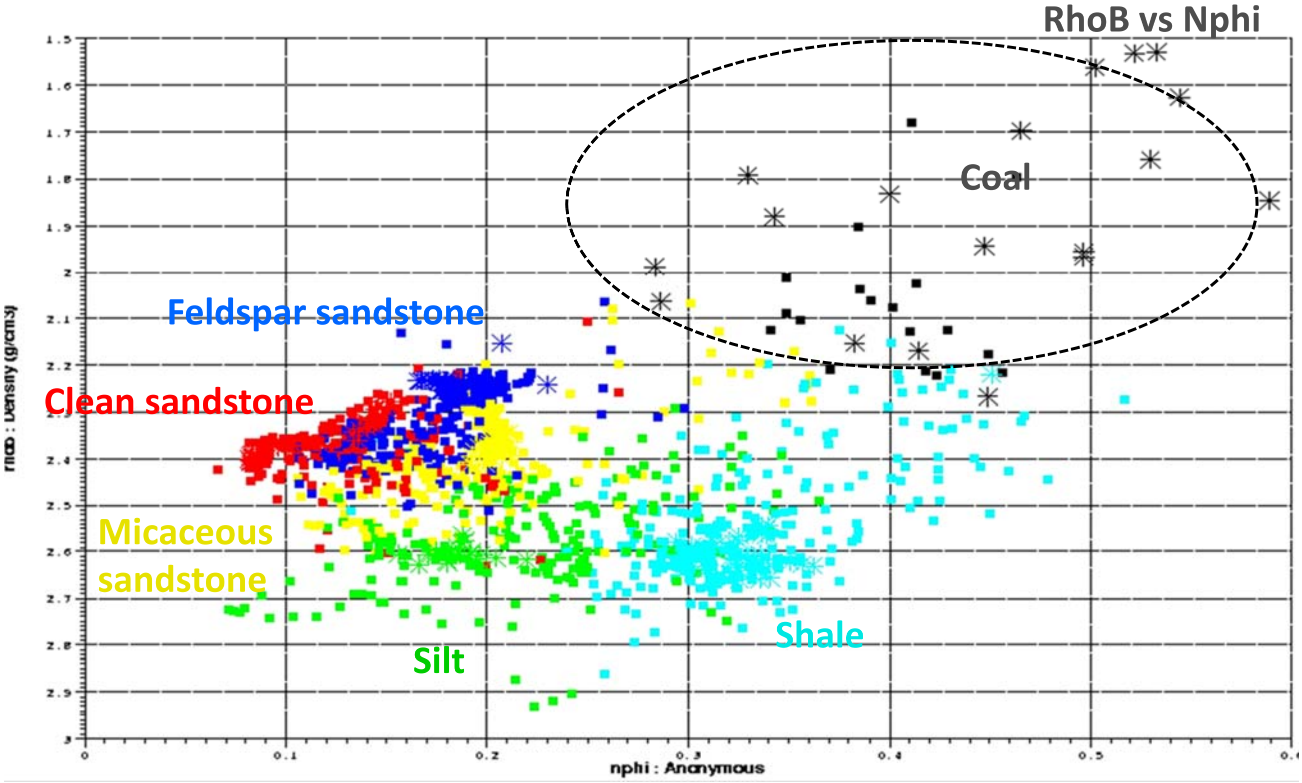
Supervised electrofacies analysis

Assignment of dataset points (non-supervised)



Supervised electrofacies analysis

Assignment of dataset points (supervised)

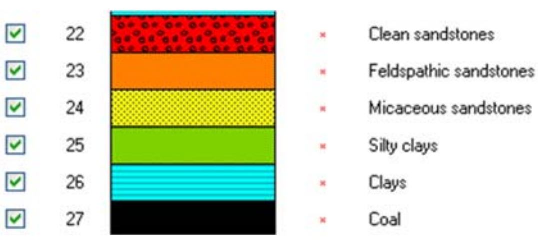


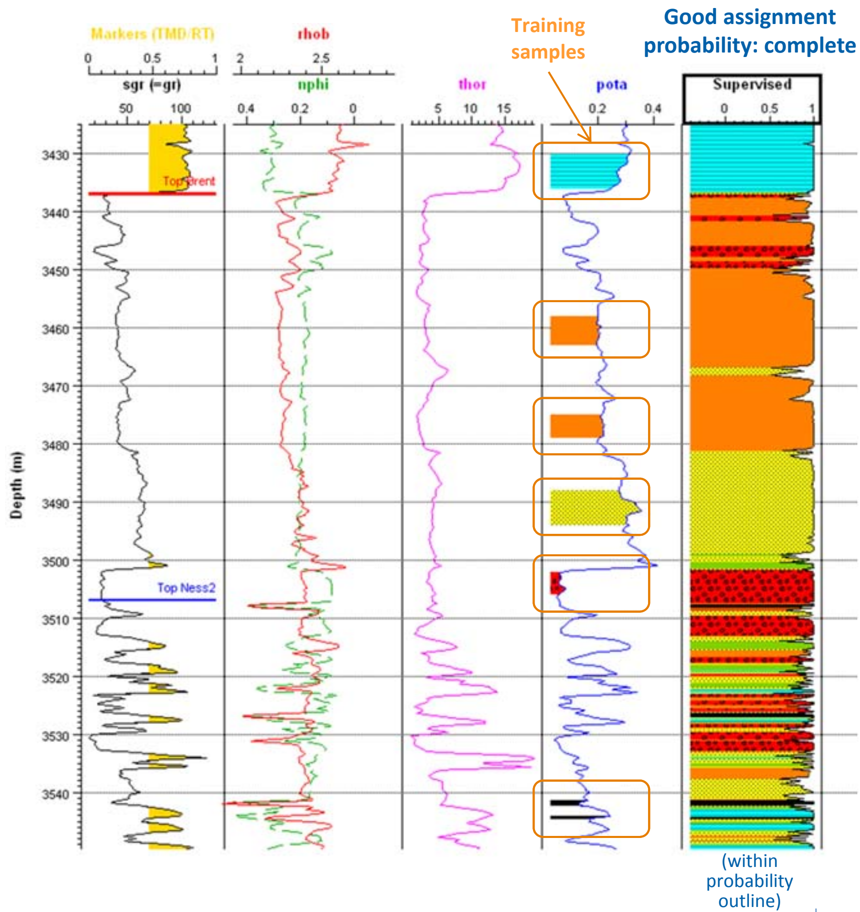
* * * * * * Training samples

Supervised electrofacies analysis

Supervised results

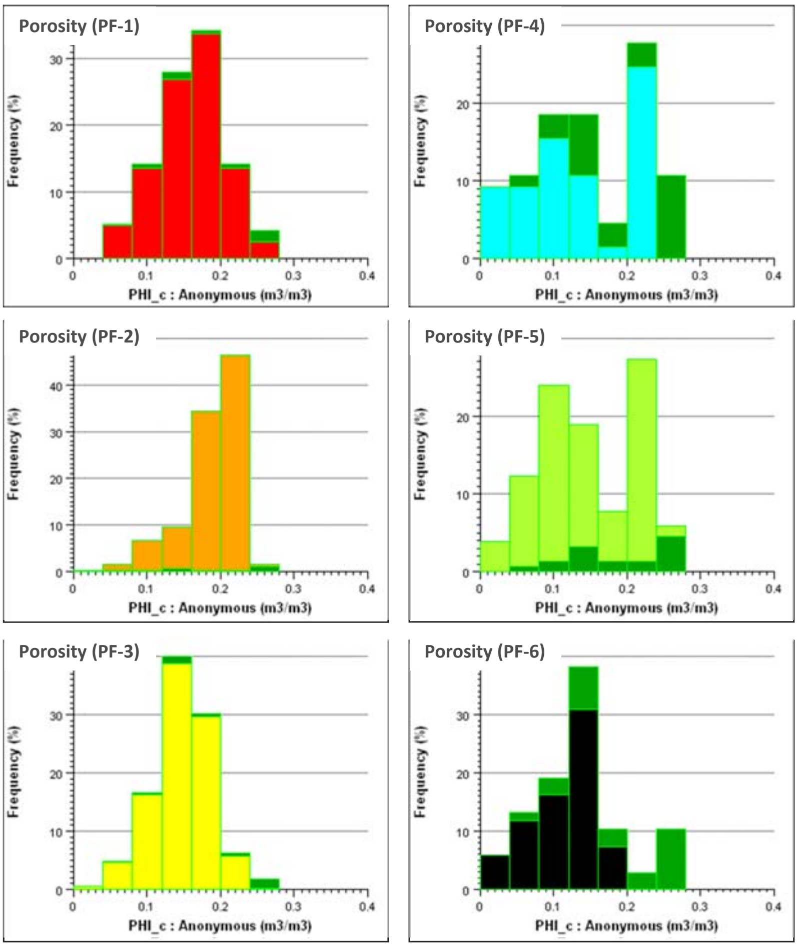
- **Results:**
  - A column of electrofacies interpreted in connection with core descriptions and/or lab measurements
  - An evaluation of uncertainty on class definition (probability of good classification)

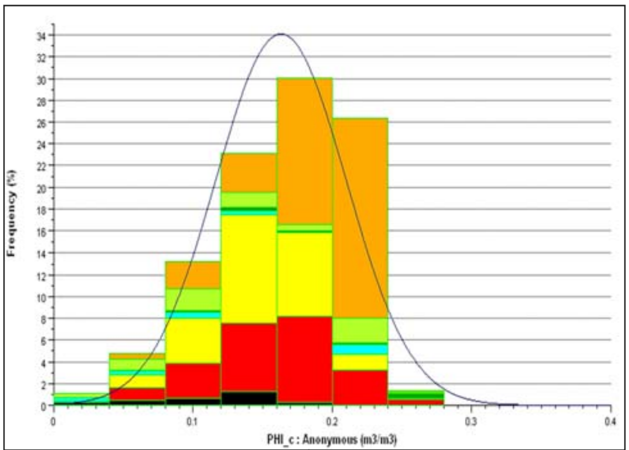


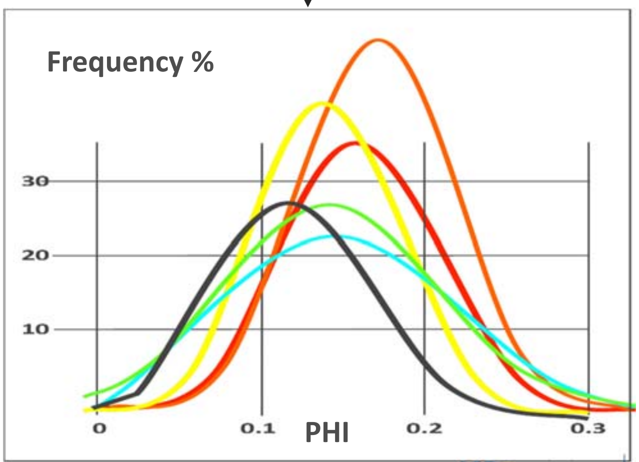


Petrofacies determination

Porosity distribution of the 6 PetroFacies

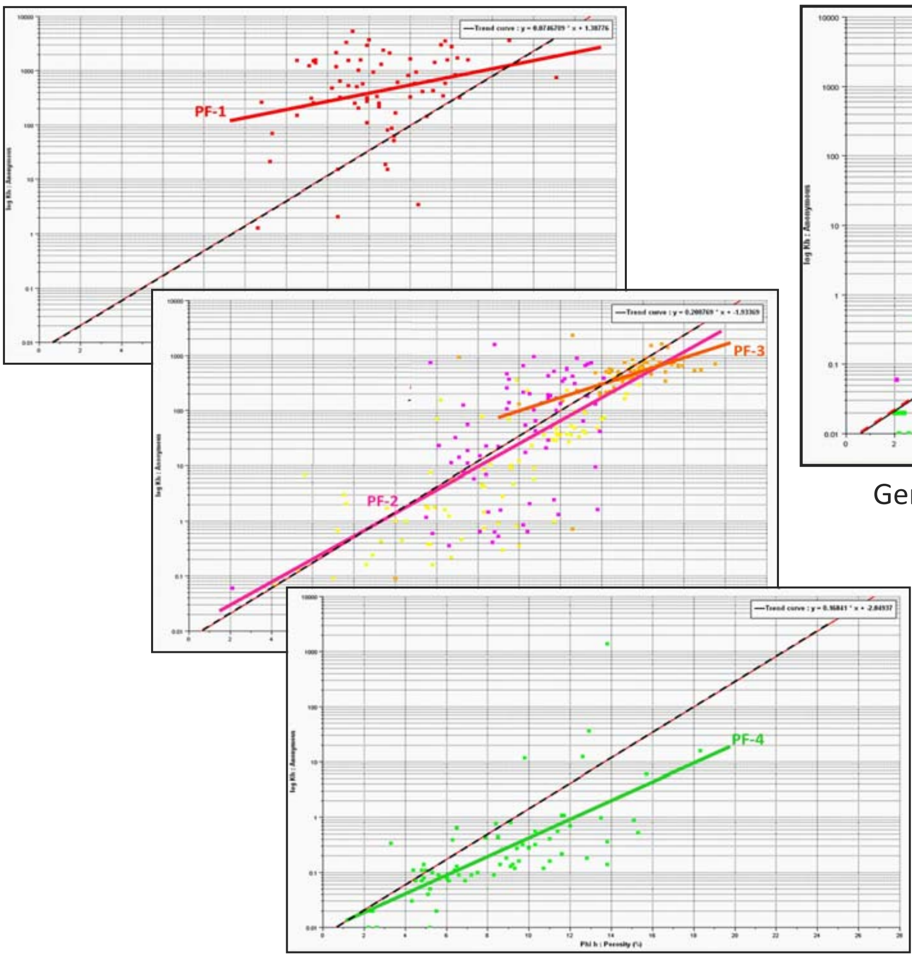


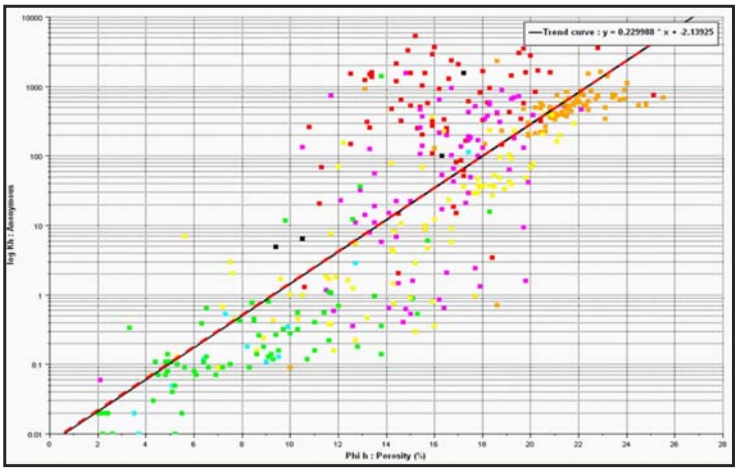




Exported from EasyTrace

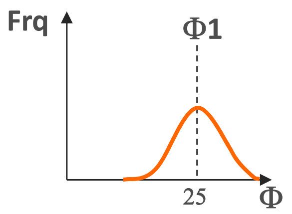
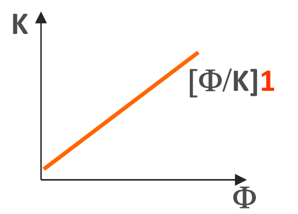
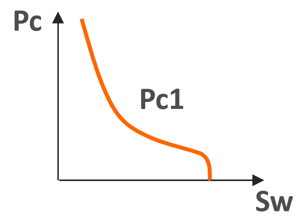
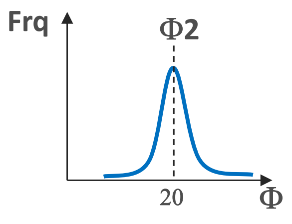
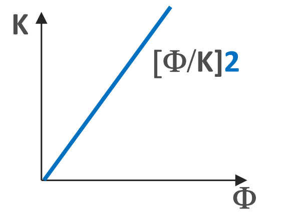
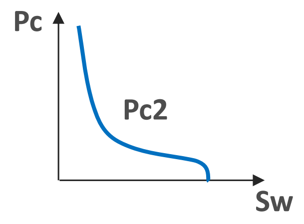
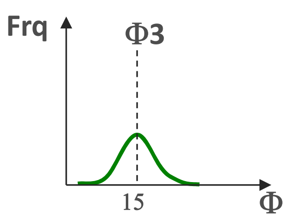
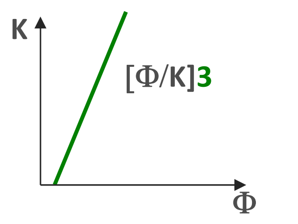
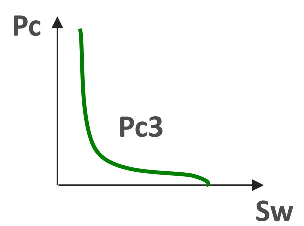
Specific Φ / K trends





General K-Phi trend (core) for all ElectroFacies

PetroFacies determination

PetroFacies	Φ	K/Φ	Pc
PF-1			
PF-2			
PF-3			

Petrofacies of calibrated Electrofacies

Rock typing - Key points

- **Integration of logs, core descriptions & petrophysical measurements (CCA or SCAL)**
  - Define the **electro-facies** tied to logs and the sedimentological facies/**litho-facies** from cores
  - Integrate petrophysics to upgrade electro-facies into **petro-facies**
  - Define the **rock types**
  - Propagate the electro-facies/rock types to non-cored wells to extend data base
- **Beware of pitfalls**
  - Is the "master" well representative of the main geological variations?
  - Are all logs QCed, depth matched and normalized?
  - Limited core information (facies, petrophysics) introduces major uncertainties when tying electro-facies to rock types
- **Electro-facies and rock types are used to populate 3D geomodels**
  - They help to define **flow units** in the upscaled dynamic model
  - They can also be correlated with 3D **seismo-facies**

10. Principles of petrophysics

Presentation summary

- Reservoir parameters: Porosity - Permeability - Saturation
- Distribution component in rock volume / Heterogeneities example
- Wettability
- Capillary pressure and pore size
- Relative permeability

Reservoir parameters
Porosity - Permeability - Saturation

Porosity – 1/2

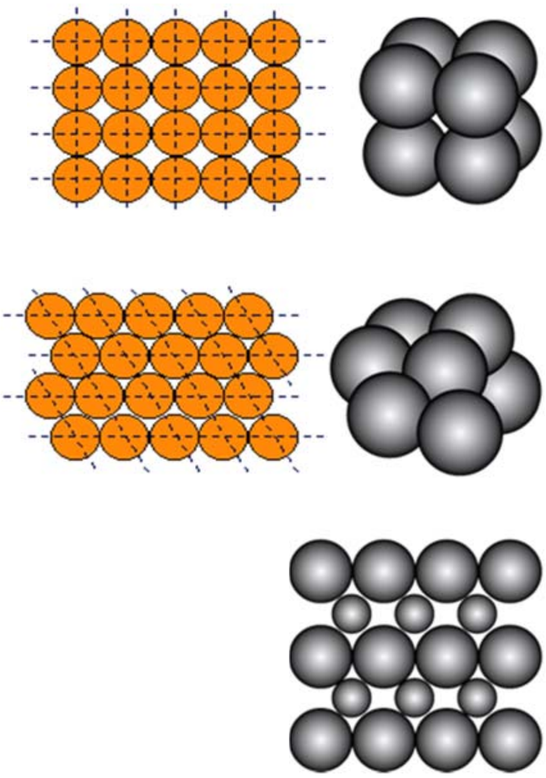
Porosity Φ

ϕ = Pore volume / Total volume

(common values 0.01 to 0.35)

Important parameters

- Grain **shape** & organization
- Grain **sorting** & distribution
- **ϕ** is not related to grain **size** *(for same size spherical grains)*



Cubical packing
(1 size)
Φ = 47.6%

Rhombohedral packing
Φ = 25.9%

Cubical packing
(2 sizes)
Φ = 12.5%

Porosity values are measured on cores and extracted from NPHI logs

Porosity – 2/2

% pores (voids) in a solid rock

$$\Phi = \frac{V_{pores}}{V_{total}} = \frac{V_{total} - V_{solid}}{V_{total}}$$

$\Phi_{effective}$ → **Lab**

Φ_{total} → **Log**

$\Phi_{effective} = \Phi_{total}$

Interconnected voids:
→ **effective porosity**
Non-connected voids:
→ **residual porosity**

Φ < 5%	**Low:** tight carbonates
10% < Φ < 20%	**Average**
Φ > 20%	**High:** poorly consolidated sandstones/chalk

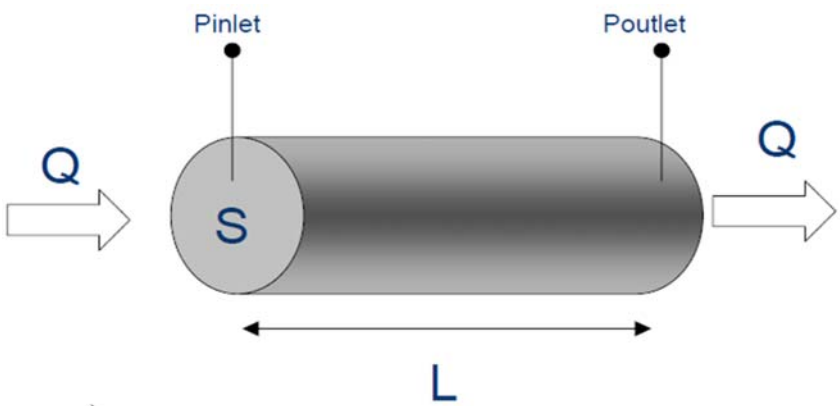
Matrix porosity → average **Φ** of fractures **< 1%** (negligible)

Permeability

- **DARCY's law (1856)**
  - **100% liquid-saturated medium**
  - **Q: flow rate** in cm^3/s
  - **S: area** in cm^2
  - **L: length** in cm
  - **K: permeability** in D
    - μ: fluid viscosity in centipoise cP
    - P: pressure in atm
    - K/μ: mobility

1 Darcy = $0.9869.10^{-12}$ m^2

$$\frac{Q}{S} = \frac{K\left(P_{inlet} - P_{outlet}\right)}{\mu L}$$



Permeability measures the ability of a rock to allow the displacement of fluids located inside the porous network: it is the **key parameter to produce a reservoir**!

Permeability data come from NMR logs, core measurements and well tests

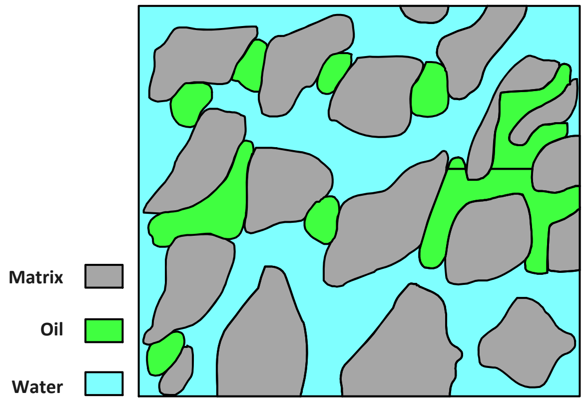
High permeability for reservoir range from 10 mD to 1000 mD, or more in fractured reservoirs.
The rock permeability varies with direction (horizontal vs vertical)

Saturation

- In reservoir studies, it is essential to know the type of fluid into the rock pores
- Rock saturation (for a given fluid) is defined by the ratio of fluid volume to pore volume, in %.

$$\mathbf{S = Fluid\ Volume/Pore\ Volume}$$

- Fluids are mainly water and can be oil and/or gas for a field:
  - Water saturation: $S_w = V_w/V_p$
  - Oil saturation: $S_o = V_o/V_p$
  - Gas saturation: $S_g = V_g/V_p$
  - And $S_w + S_o + S_g = 1$
- Saturation data come from well log analysis (Resist./Induct. + Archie) and core analysis

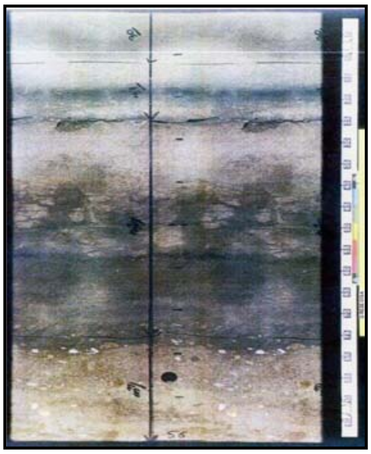


Thin section showing oil saturation

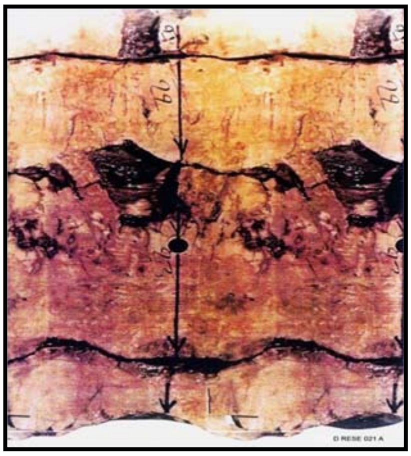
Distribution component in rock volume

Examples of heterogeneities

Reservoir heterogeneities



Sandstone with shale baffles



Intense network of small impregnated fractures (carbonate)

Stylolites (carbonates)

K↓

Dissolution in karst (super K)

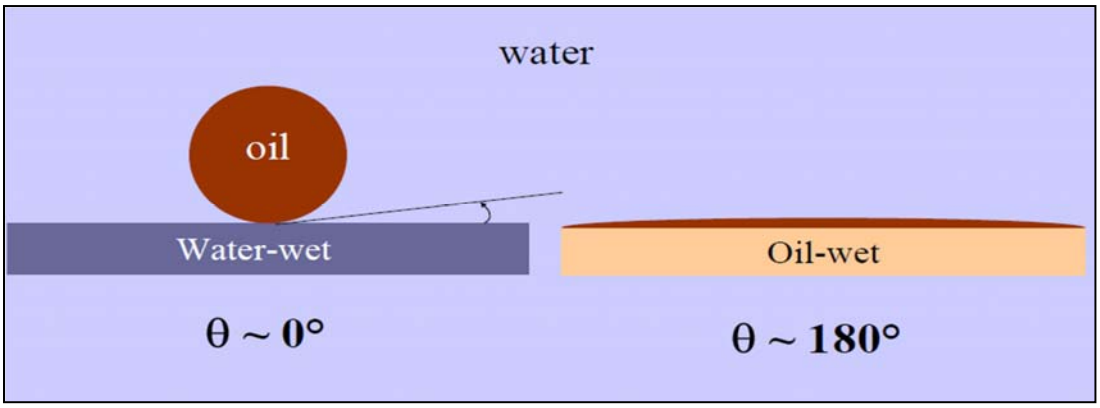
K↑

Wettability

Wettability – 1/2

On a flat surface

Wettability = Tendency of a fluid **to spread on or to adhere to** a solid **surface** in presence of another **immiscible** fluid



- **Wetting fluid: contact angle Θ < 90^o**
- **Wettability to oil due to polar components in oil or to adsorbed products on rock surface**
- **In a rock/brine/oil system, wettability measures the rock preference for either oil or water**

Wettability of a porous medium

- **The wettability determines which fluid will be in contact with the rock surface**
  - Water-wet rock: water covers rock surface, oil occupies the bulk of larger pores.
  - Oil-wet rock: oil covers rock surface, water occupies the bulk of larger pores.
  - Intermediate-wet or neutral-wet: no preference for either fluid.
  - Gas is always non-wetting!

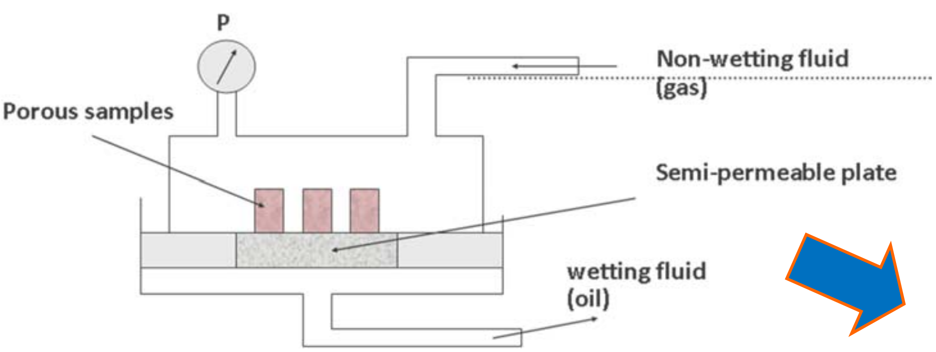
- **Wettability plays a major role on fluid distribution within the pore structure and, consequently, on the behavior of rock fluid systems during flow (i.e. oil or gas)**

- **Thus, wettability affects:**
  - Relative permeabilities
  - Capillary pressures
  - Residual saturations

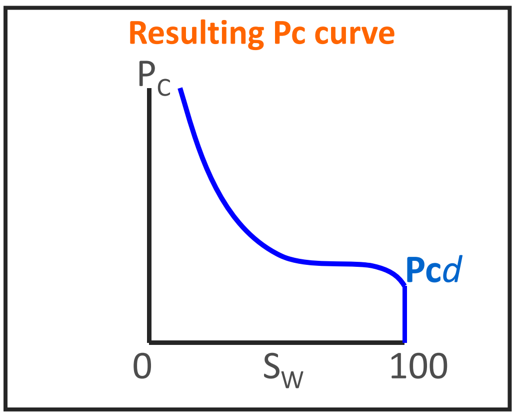
Capillary pressure vs. Pore size

Capillary Pressure definition and measurement

- **Capillary Pressure is the difference in pressure within a capillary medium between the non-wetting phase and the wetting phase**
- **Lab measurement**
  - Displacement of wetting fluid by non-wetting phase with increasing pressure (i.e. drainage)



Rock samples from core
Fluid W/G measured in lab condition



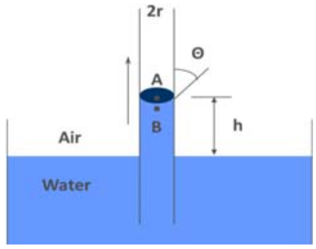
- **Capillary Pressure**
  - Characterizes the porous network
  - Affects the fluid distribution in the porous medium
  - Affects the fluids production

Pcd: displacement pressure

Capillary Pressure curve

- **Modeling porous media with a bundle of capillary tubes of different radii**

$$P_C = h\,\Delta\rho g = \frac{2T\cos\theta}{R}$$

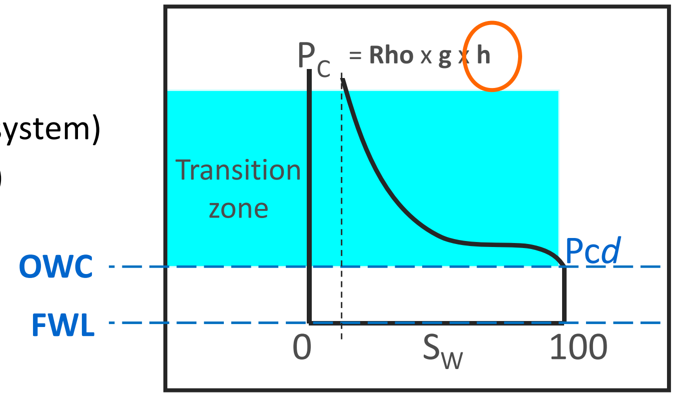


- To a given P_C corresponds a radius **R**
- All pores with radius **r < R** are filled with the wetting phase (water)

→ Variation of P_C as a function of S_W defines the **Capillary Pressure curve**

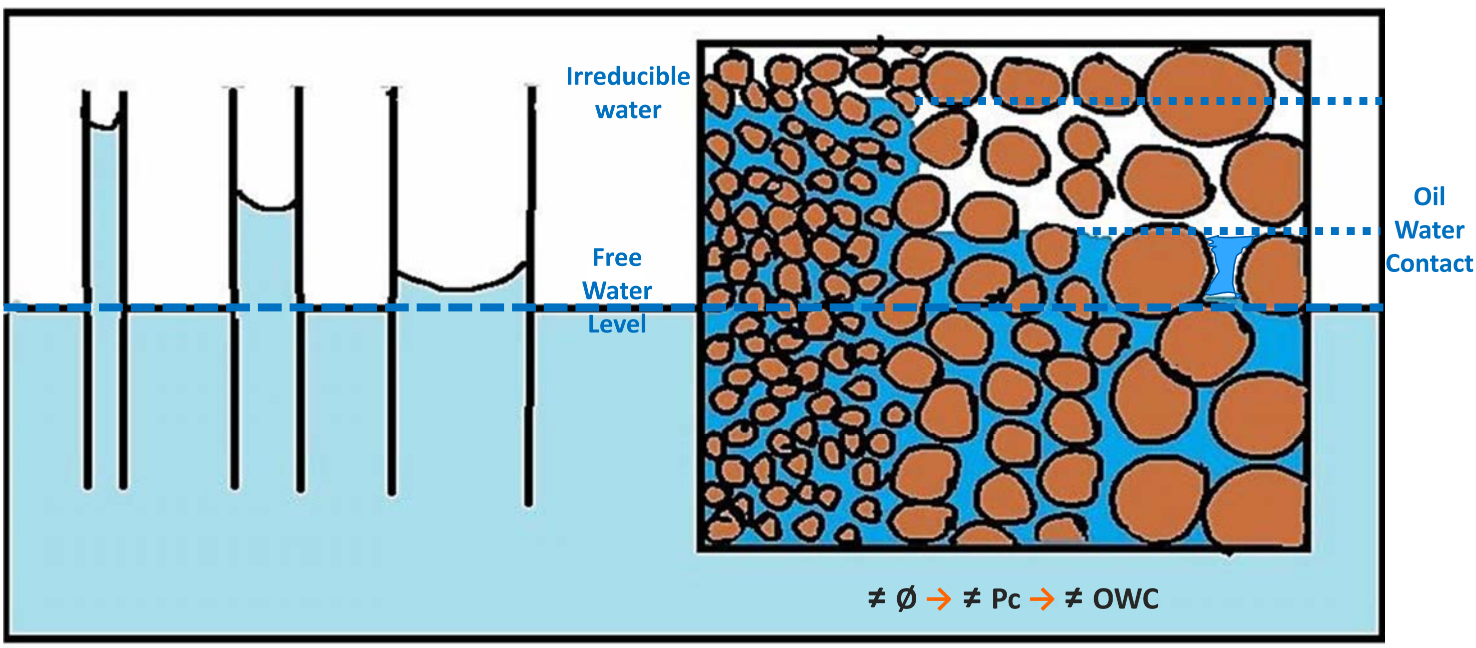
- **Capillary Pressure depends on**
  - Pore size (medium)
  - Wettability (medium & fluid system)
  - Surface tension (fluid system)
- **In reservoir conditions:**

  → **H (in m) vs. Sw**



Displacement Capillary pressure

Capillarity and fluid distribution



Fluid level references in a reservoir

Transition zone

- **Evaluation from a P_c curve**
  - P_c obtained in laboratory
- **Correction for reservoir conditions**
  - $P_c(h) = \Delta\rho \times g \times h$ from (zero Pc depth)
  - $P_c(S_w)$ known

- **Threshold P_c**: value at which oil first enters pores (S_w<1) [P_c displacement]
- **Free water level** (FWL): depth at which $P_c = 0$
- **Oil-water contact** (OWC): depth below witch no oil can be found

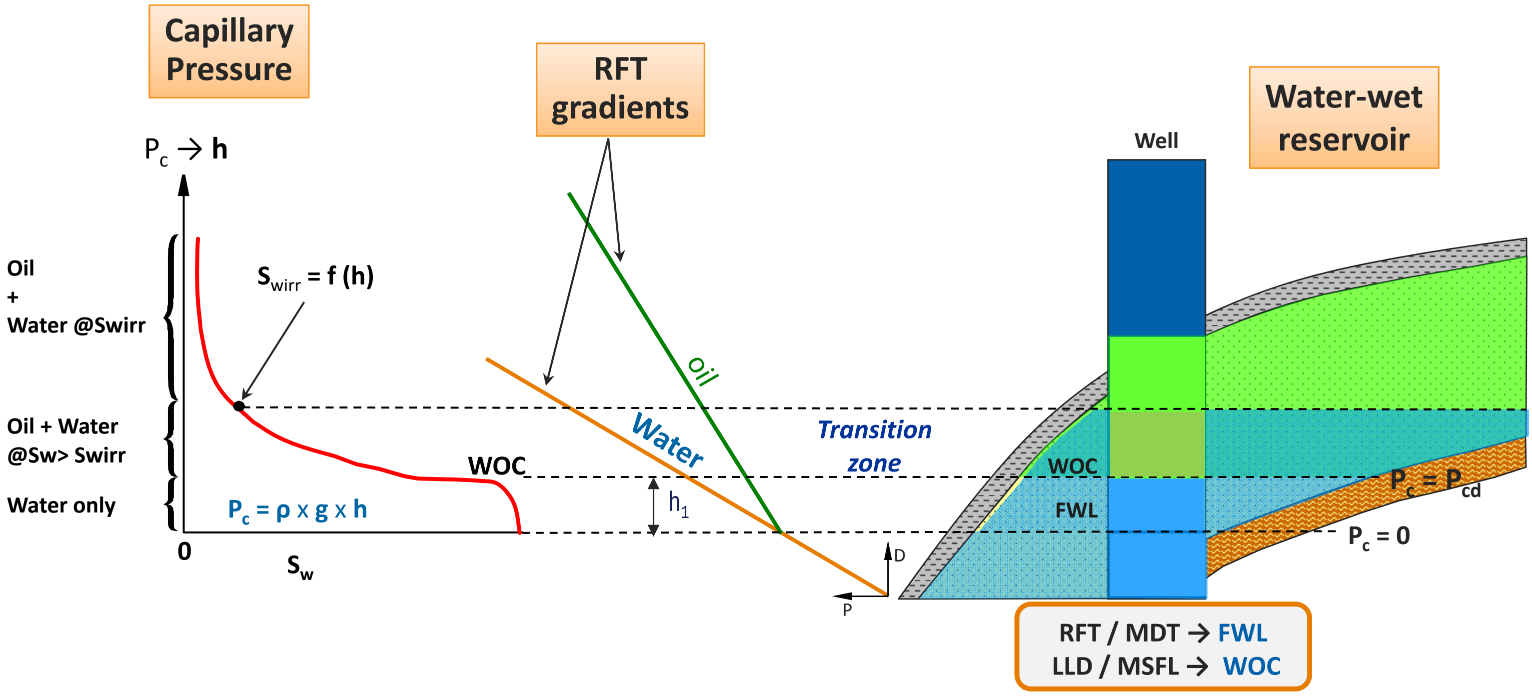
$S_w = f(h)$
accumulations

If reference depth is **FWL** → $P_c = \Delta_\rho \times g \times h$

If reference depth is **WOC** → $P_c - P_{cd} = \Delta_\rho \times g \times h$

Capillary Pressure

Capillary Pressure and fluid distribution in the reservoir

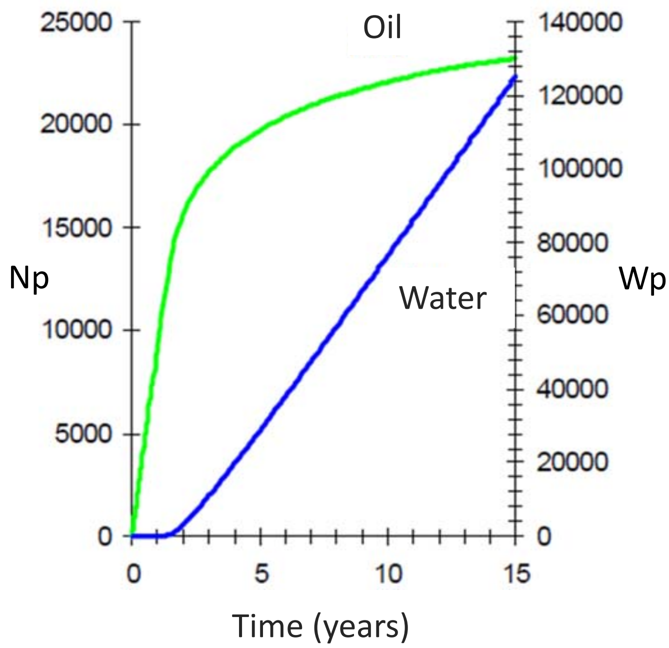


FWL = **Free Water Level** → $P_c = 0$

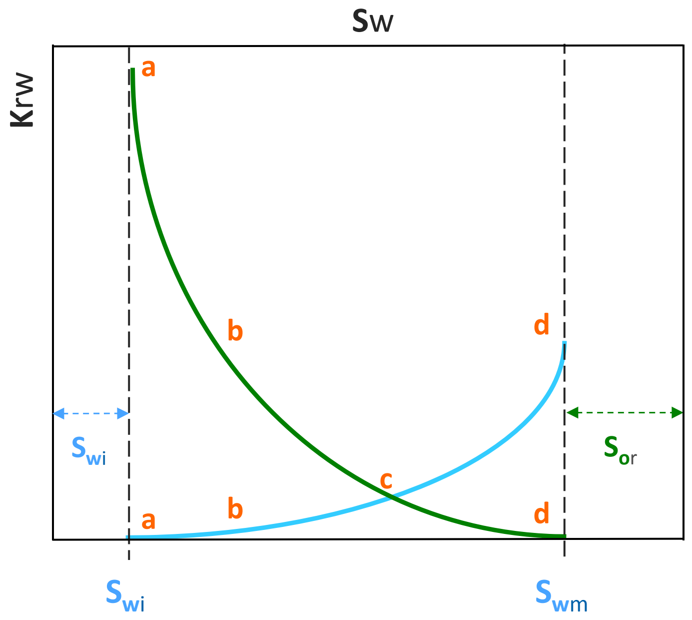
WOC = **Water-Oil Contact** → $S_w = 1$ **corresponding to displacement pressure** $P_{cd} = \Delta\rho . g . h_1$

Relative permeability and multiphase flow – Why?

- **Most of the oil or gas recovery is achieved while multiphase flow occurs in the reservoir**
- **Two or three fluids are frequently produced simultaneously at surface and are usually simultaneously mobile in the reservoir**
  - => Multiphase flow in porous media
  - Production rate of each of these fluids varies with time:
    - How can we forecast production rate versus time?
    - Through the concept of relative permeability



Relative permeability (K_r) - Oil vs. Water example



a: only **oil** is moving: $K_{ro} = 1$ and $K_{rw} = 0$

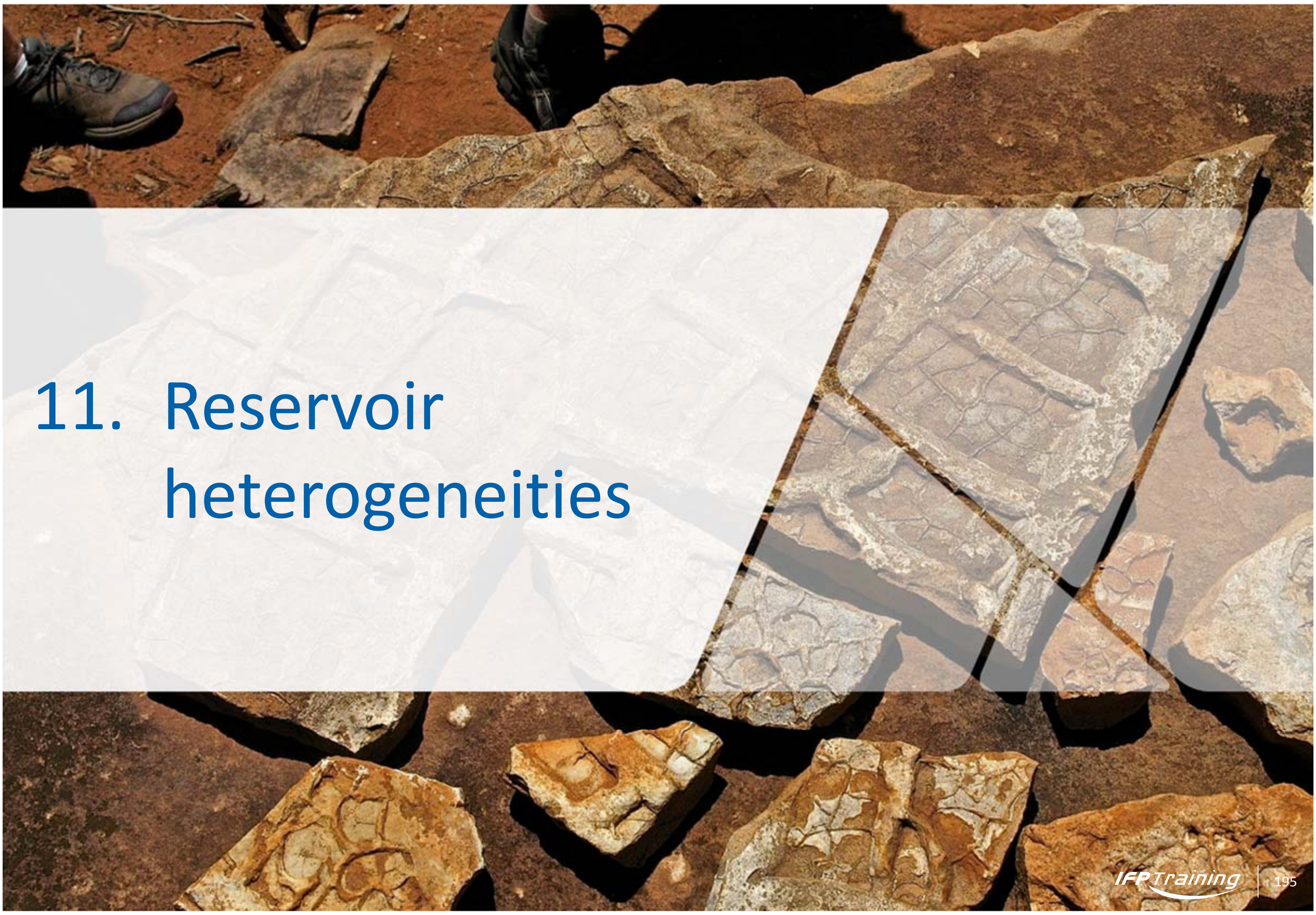
b: $S_w \nearrow$: oil flows less easily

c: $K_{ro} = K_{rw}$ and $K_{ro} + K_{rw} < 1$

$$K_{2\ phases} < K_{1\ phase}$$

d: oil is not mobile any more ($S_o = S_{or}$), $K_{rw}(S_{or}) < 1$
only **water** is moving

- These curves dictate the diphasic flow of oil and water in the reservoir and are used for reservoir simulation
- Except possibly for end points, the sum of relative permeabilities is always strictly lower than 1 => diphasic flow is always less efficient than monophasic flow



11. Reservoir heterogeneities

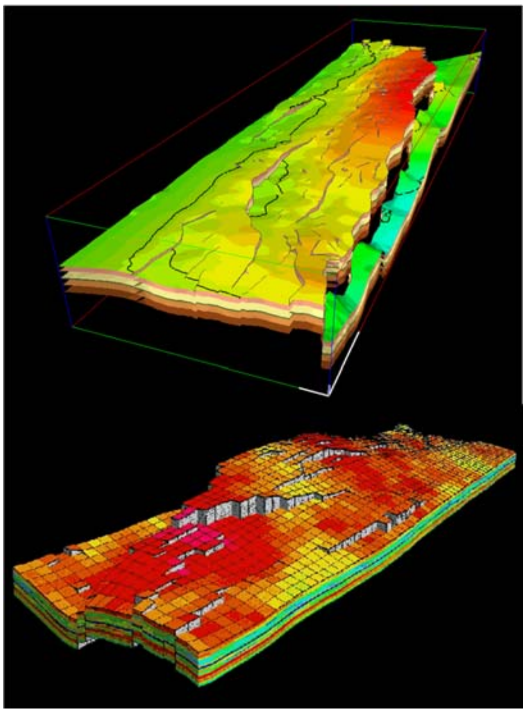
Reservoir heterogeneities

Summary

- **Introduction: heterogeneities in the reservoir**
  - Homogeneous/heterogeneous reservoirs
  - Reservoir heterogeneity concepts
  - Classification of reservoir heterogeneities
  - Impact of reservoir heterogeneity on hydrocarbon recovery
- **Reservoir heterogeneity features**
  - Scale of reservoir heterogeneities
  - Small-scale observation and analysis
  - Large-scale observation and analysis

Homogeneous vs. Heterogeneous reservoir

Homogeneous reservoir



Heterogeneous reservoir
(Layers, Facies, Faults, Unconformities, Diagenesis, Fracture swarms, Super K,…)

Heterogeneity: spatial variation of rock physical properties affecting fluid flow

→ Non-homogeneous reservoir sweeping

Reservoir heterogeneity

- **To build a consistent and relevant model:**
  - all variations in the reservoir quality must be analyzed and classified so that the main heterogeneities are clearly highlighted
  - for a given study, all heterogeneities that can affect fluid flow are considered as key heterogeneities

→ Key heterogeneities have to be absolutely described in the geological model

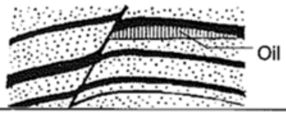
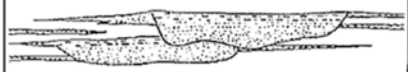
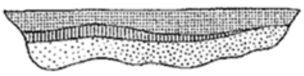
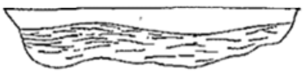
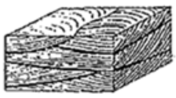
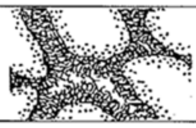
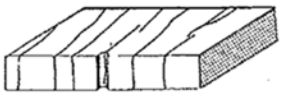
- **Reservoir heterogeneities**
  - All relevant factors affecting the dynamic behavior of the field
  - Small- to large-scale geologic features
  - From static reservoir characterization (significant or not)
  - From dynamic reservoir characterization (significant)
- **Basic principle**
  - Identify the smallest element that might impact production

Characterizing reservoir heterogeneities calls for the cooperation between all professionals involved in the study (i.e. from geophysicists to reservoir engineers)

Classification of reservoir heterogeneities

Weber classification (1986)

"How heterogeneity affects oil recovery"

	Reservoir heterogeneity type		Heterogeneity ranking
A: Structural	Sealing fault Semi-sealing fault Non-sealing fault		1 to 3
B: Stratigraphic	Boundaries genetic units		1 to 3
C: Diagenetic	Permeability zonation within genetic units		1 to 3
D: Depositional	Baffles within genetic units		1 to 3
E: Depositional	Lamination, cross-bedding		1 to 3
F: Diagenetic	Microscopic heterogeneity, textural type, mineralogy		1 to 3
G: Structural	Fracturing tight, fracturing open		1 to 3

Prior to the modeling phase, it is necessary to perform a **synthesis of heterogeneity types**, for each item, taking their **impact on fluid flow** into account , by using the following ranking:

1 - major heterogeneity
2 - intermediate heterogeneity
3 - negligible heterogeneity

Classification objective: to highlight the most significant heterogeneities.

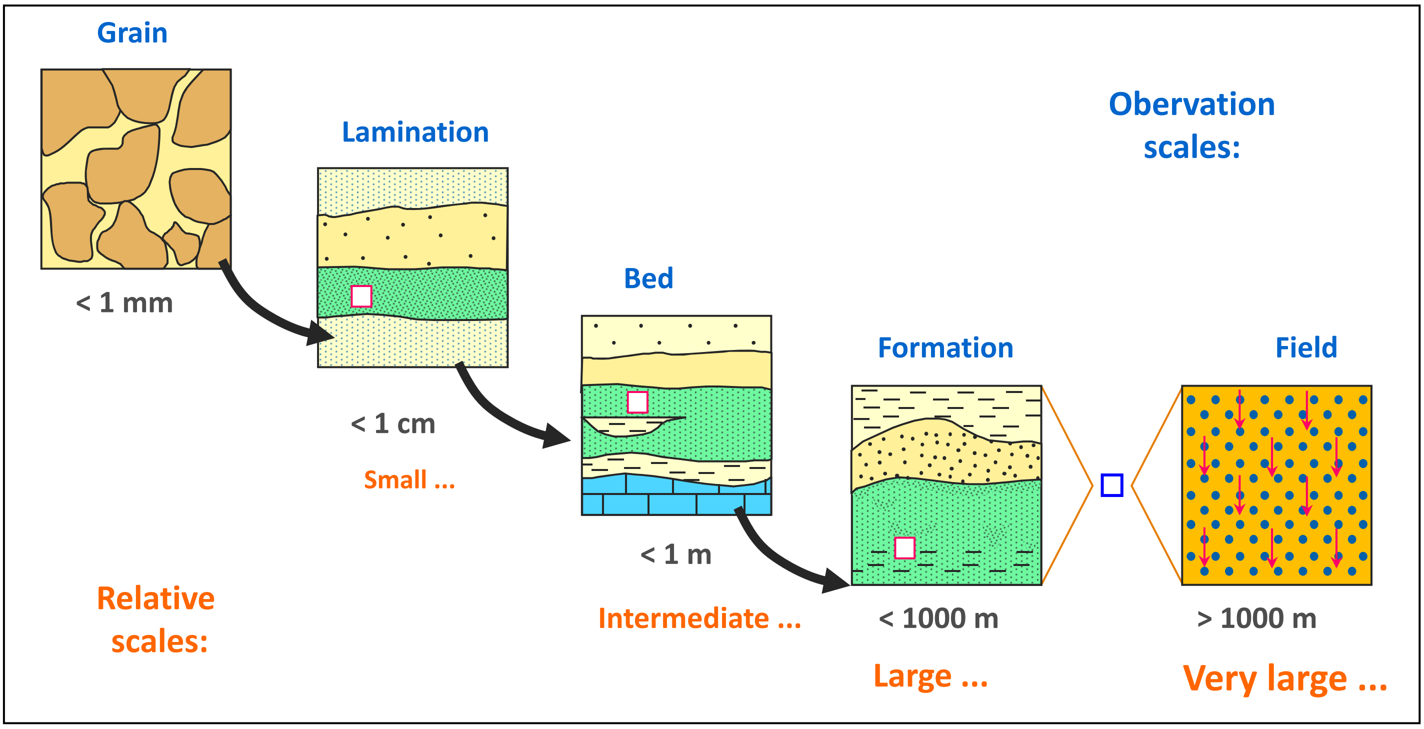
Impact of reservoir heterogeneities on recovery

Impact of reservoir heterogeneity type for oil recovery

Reservoir heterogeneity type	Reservoir continuity	Sweep efficiency		
		Horizontal	Vertical	Microscopic
Large scale				
Sealing fault	×	×		
Partially sealing fault	o	×	×	
Non-sealing fault	o	×	×	
Boundaries of genetic units	×	×	×	
Permeability zonations		o	×	o
Baffles and streaks		o	×	o
Open fractures		×	×	
Tight fractures		×	×	
Small scale				
Laminations and crossbedding		o	o	×
Mineralogy and texture			×	
Open microfractures		×	×	×
Tight microfractures		×	×	×

o = moderate effect × = strong effect

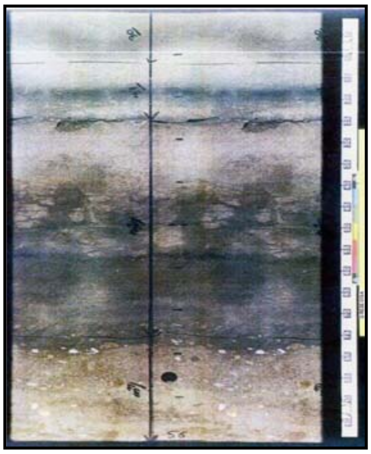
Scale of reservoir heterogeneities



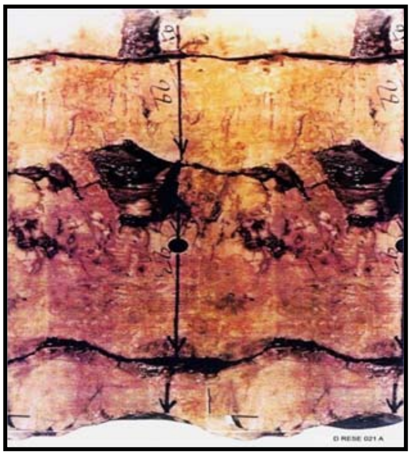
(from Krause and Collins, 1984)

Heterogeneities and investigation tools do not always have the same scale...

Small scale: Reservoir heterogeneities



Sandstone with shale baffles



Intense network of small impregnated fractures (carbonate)

Stylolites (carbonates)

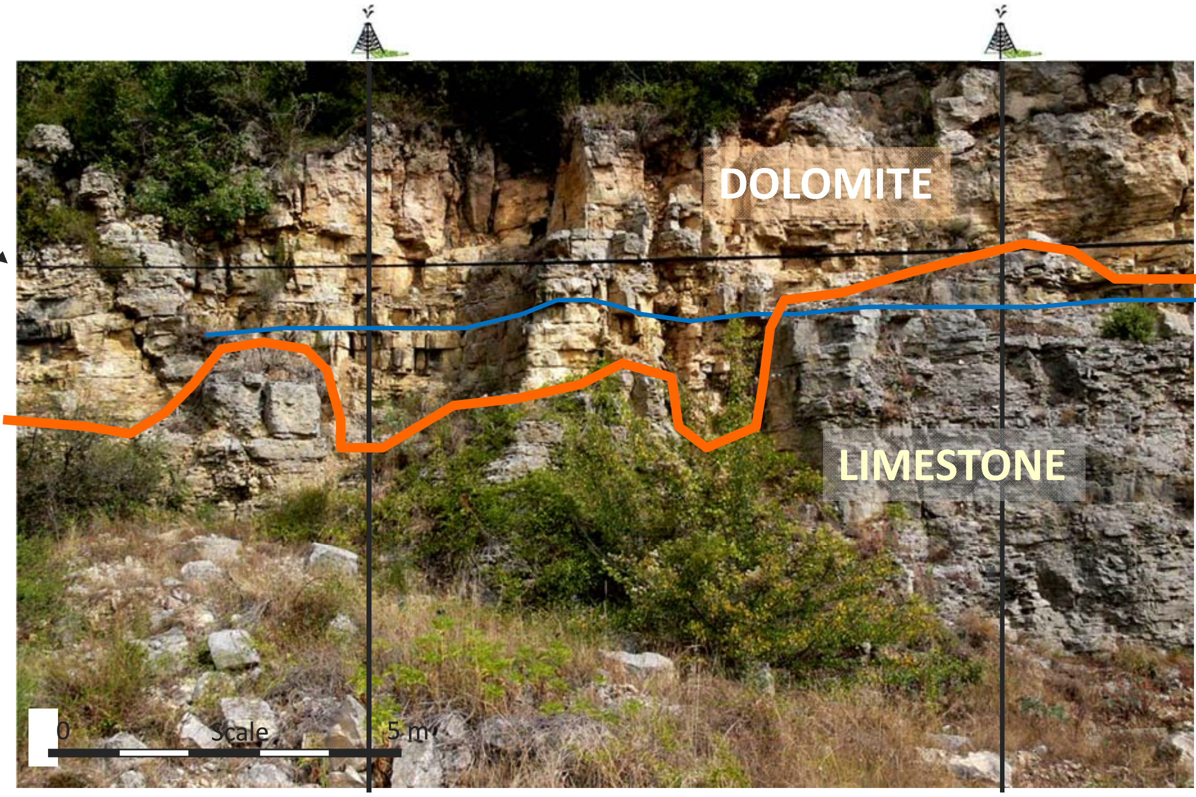
K↓

Dissolution in karst (super K)

K↑

Large-scale heterogeneities

Diagenesis

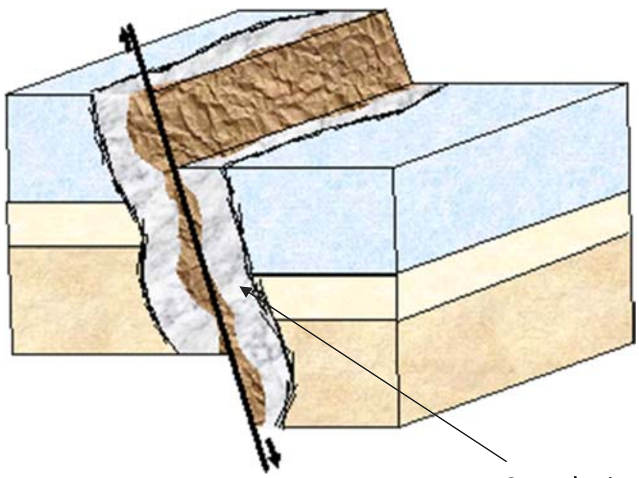


Large-scale heterogeneities (1/5)

[redacted] Clay smear mechanism.

Faults

- **Juxtaposition** of reservoir units and low permeability units
- **Clay smearing** (injection of clay into the fault plane)
- **Cataclasis**: sand grains crushing
- **Diagenesis** (fault-related): cementation that creates hydraulic seals



Reservoir characterization and modeling - Key points

- **To build a consistent and relevant model for an integrated study:**
  - All reservoir heterogeneities must be identified and classified (main ones highlighted)
  - All heterogeneities that can impact fluid flow are considered as major heterogeneities
  - Even the smallest elements that can affect production need to be identified and modeled
  - The geological model must take all significant heterogeneities into account
  - The characterization of reservoir heterogeneities calls for an integrated multi-disciplinary approach (cooperation and team work)

12. Reservoir Characterization

Characterization step

Main ideas

- **Perform a data analysis to understand the reservoir before modeling**
- **Do not model anything if you do not have an idea of the results you want to reach!**

Tools for characterization

All tools for quality control and data analysis are reliable

- **Geology**
  - Core description
  - Log analysis (correlation, sequence stratigraphy, electrofacies)
  - Statistical data analysis
  - Geostatistical data characterization
- **Geophysics**
  - Conventional seismic facies analysis
  - Seismic quality synthesis using geostatistics
  - Seismic facies analysis

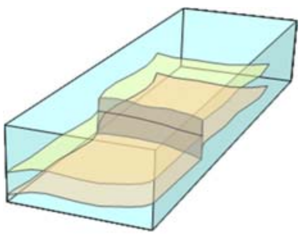
Structural and Stratigraphic models

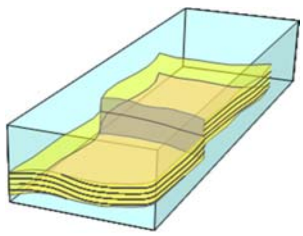
Structural model

- **Objectives**
  - To identify the trap structure
  - To define the reservoir architecture
  - To determine:
    - Horizon shape, continuity
    - Fault network
- **Based on**
  - Seismic data
  - Well data

Stratigraphic model

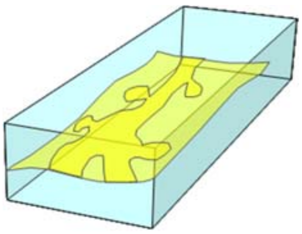
- **Objectives**
  - To identify the reservoir layering
  - To determine the modeling parameters
- **Based on**
  - Seismic (stratigraphic analysis)
  - Well log
    - Analysis, correlation
  - Core (stratigraphic description)





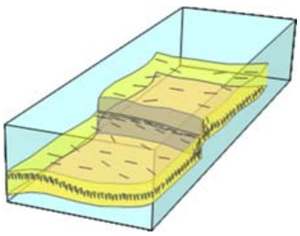
Sedimentological model

- **Objectives**
  - To describe the depositional environment
  - To determine the modeling parameters
- **Based on**
  - Seismic (attribute analysis)
  - Well log
    - Analysis, correlation
  - Core (facies description)
  - → Facies classification
  - → Statistical analysis (Vertical Proportion Curve)



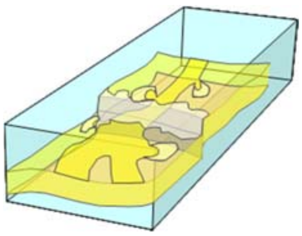
Fracture model

- **Objectives**
  - To identify fractured area
  - To determine modeling parameters
    - discrete fracture network (DFN)
- **Based on**
  - Seismic (attributes)
  - Well logs
    - Borehole imaging
  - Core (fracture analysis)
  - Dynamic data



Diagenetic model

- **Objectives**
  - To identify the diagenesis vectors
  - To determine the modeling parameters
- **Based on**
  - Seismic (attributes)
  - Well logs
  - Core (diagenesis description)



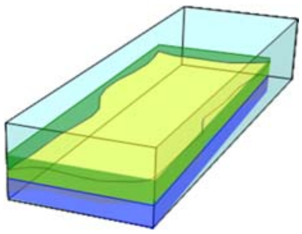
Fluid and Heterogeneity models

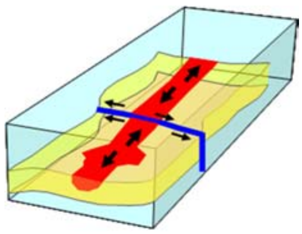
Fluid model

- **Objectives**
  - To determine the fluid contacts
  - To determine the modeling parameters
- **Based on**
  - Well logs (contacts)
  - Core (petrophysical analysis)
  - Dynamic data
  - PVT

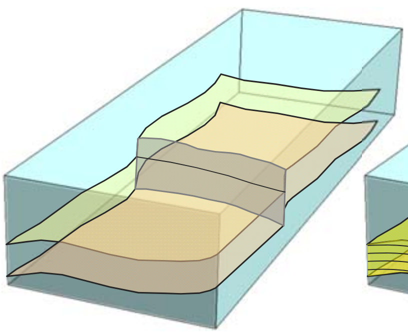
Heterogeneity model

- **Objectives**
  - To describe the key heterogeneities
  - To quantify the impact on fluid flow
  - To help reservoir engineer for simulation
- **Based on**
  - Seismic
  - Well logs
  - Cores
  - Dynamic data

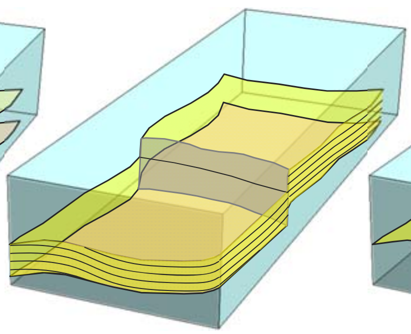




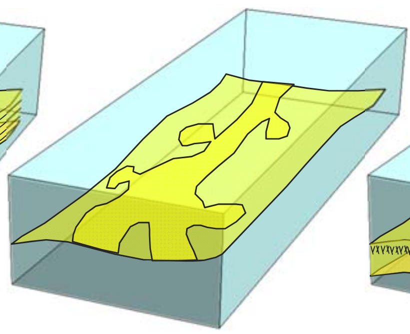
Results: Conceptual models as leads for modeling



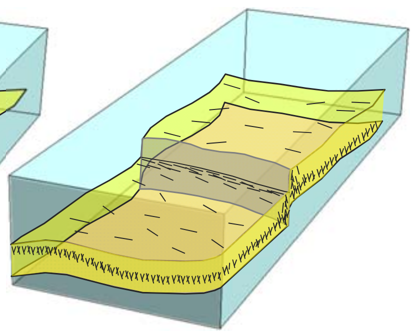
Structural model



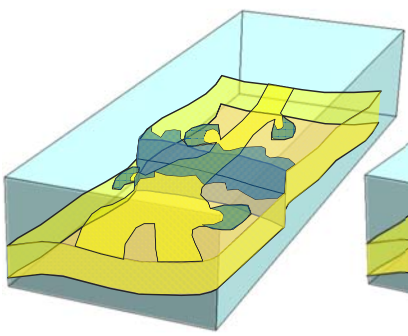
Stratigraphic model



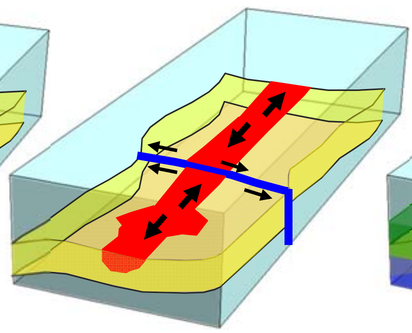
Sedimentological model



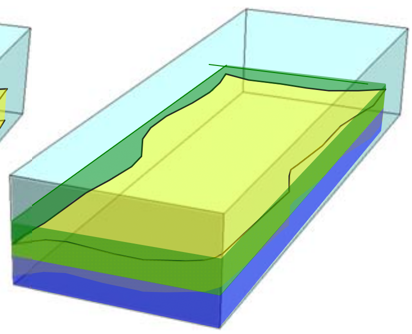
Fracture model



Diagenetical model



Fluid flow model
Heterogeneity

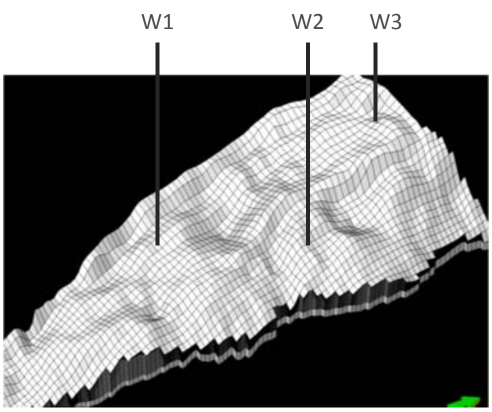


Fluid model

13. Reservoir modeling

Which data?

Initial step

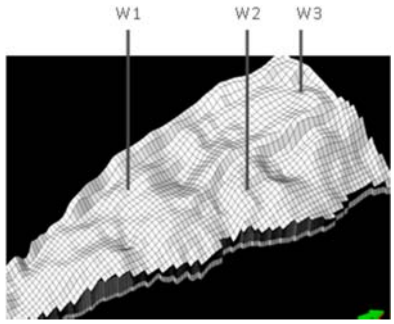


* **Data** only available at the intersection between model and well trajectory

* **Data:**
  - Net-to-Gross
  - Porosity
  - Permeability
  - Saturation
  - Litho-facies / Petro-facies
  - Electro-facies
  - Rock Type

Which tools?

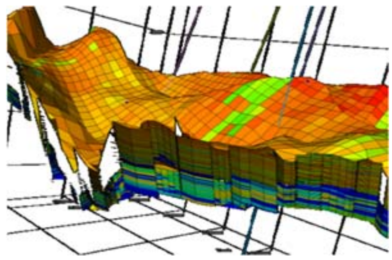
Initial step



Data only at the intersection between model and well trajectory

Porosity
Permeability
Litho-facies
Electro-facies
Petro-facies
Rock type

Final step

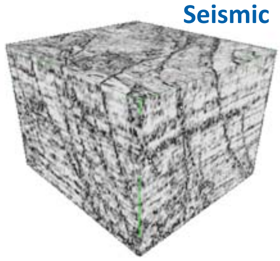


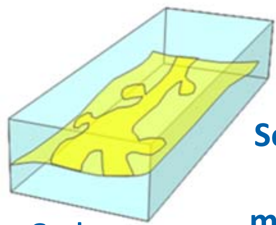
Petrophysical data

Mapping tools

Geostatistical tools

Seismic





Geology

Source data that can be used **to constrain mapping** or geostatistics

Geostatistical tools

- **Statistics**
  - Branch of applied mathematics concerned with
    - **quantitative data** collection and interpretation
    - the use of the **probability theory** for quantitative estimation of the population-related parameters
- **Geostatistics**
  - Branch of statistics that applies to **spatially distributed data**

Objective of geostatistics: to populate data between wells

14. Conclusion

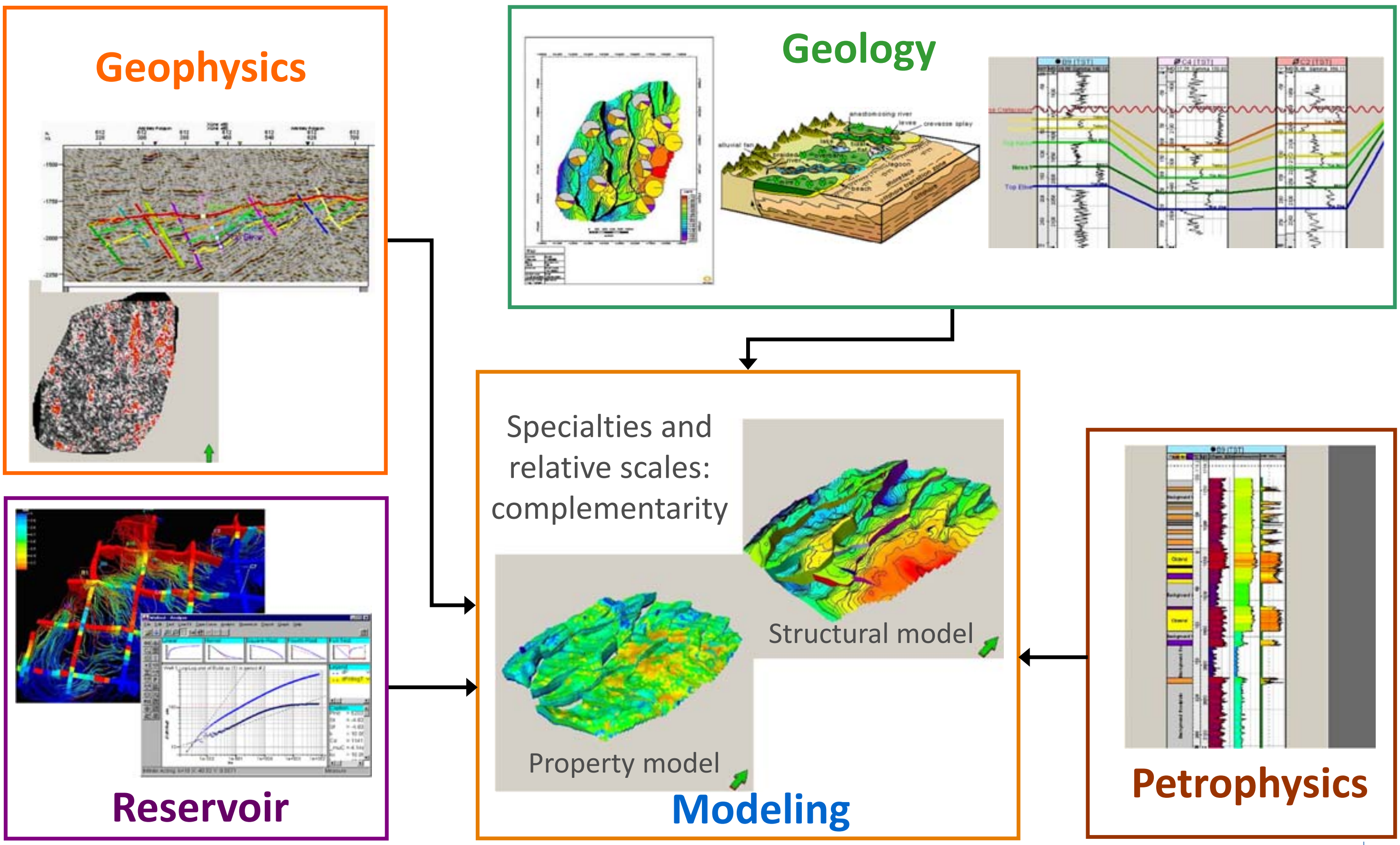
How to model experience.?.

- **Imbricate notions**
  - Understand
  - Characterize
  - Model

→ **Simplify to understand the complexity of nature, and model it to quantify it**

→ ***A model is more simple and more sensible…***

Reservoir Modeling = Integration!



Reservoir modeling objectives - Key points

- **Reservoir model* construction is the main objective of an integrated reservoir study.**
- **This model is used to simulate field evolution over time for:**
  - well production
  - fluid displacements (within the reservoir)
  - pressure evolution
- **The geomodel¤ represents one of the most important phases in an integrated reservoir study workflow, because:**
  - it integrates **reservoir geometry** and **petrophysical properties**
  - it takes **dynamic information** into account
  - it provides **key heterogeneity** for modeling

* Reservoir model = **Dynamic model**
¤ Geological model = Geomodel = Geocellular model = **Static model**

Thank you for your attention and participation